Northwestern University
HEP Seminar
October 3, 2016

ADMX-G2: an Axion Dark Matter Radio

Aaron S. Chou
FNAL

ADMX-G2 goals

1. Discover particle (wave-like) dark matter by direct detection.

2. Test the Peccei-Quinn solution to the strong-CP problem.

3. Probe a large region of the “classic window” for axions.

Do the above using demonstrated technology* that is available today.

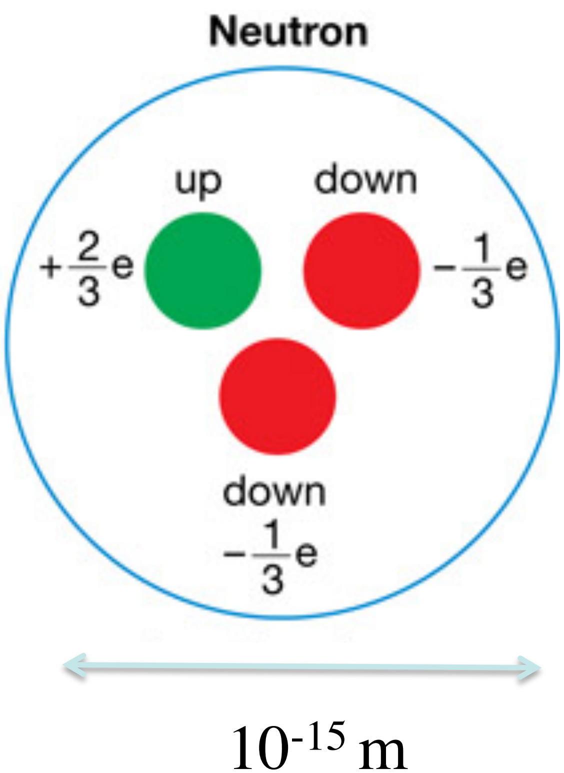
ADMX-G2 is the **only** operating experiment with sensitivity to QCD axions.

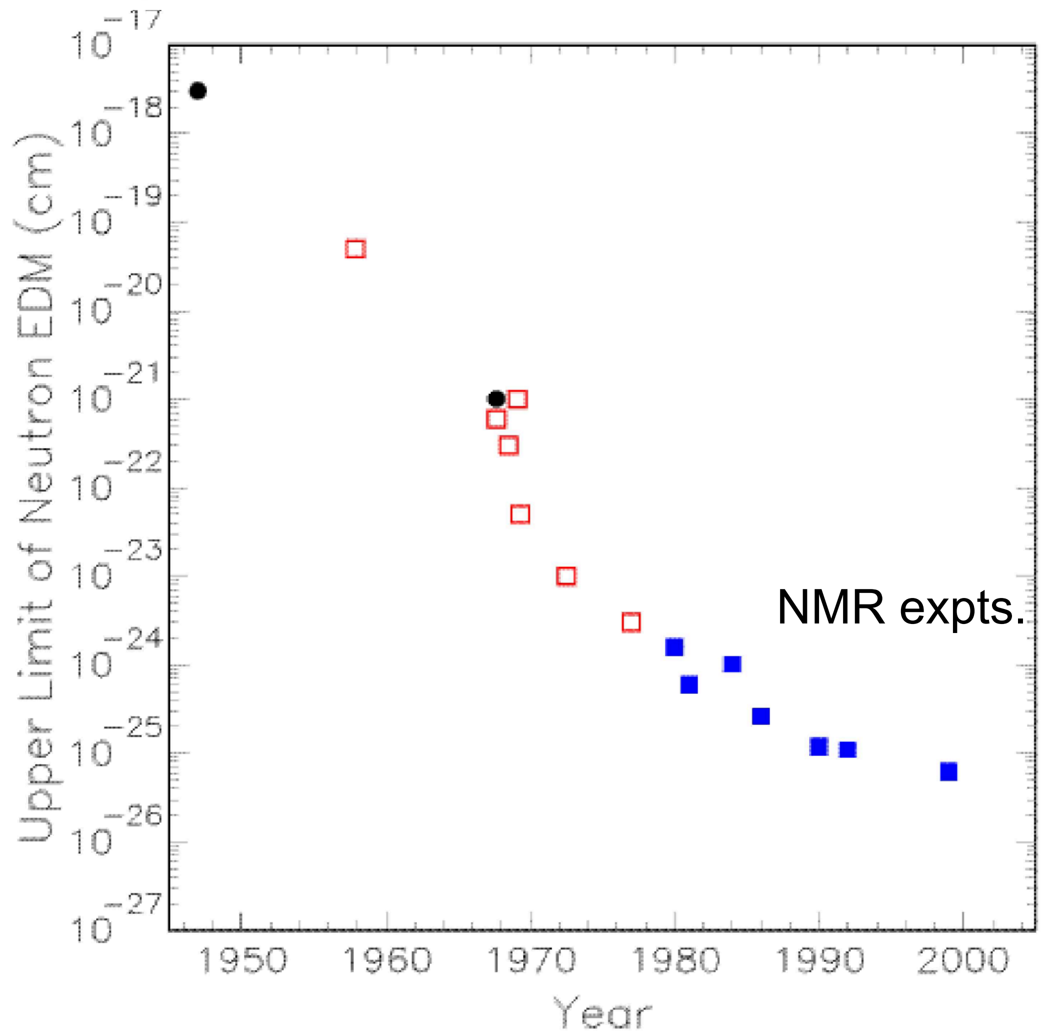
*Quantum-limited amplifiers, 100 mK dilution refrigerator

Q: Why is the neutron electric dipole moment so small?

ADMX AXION DARK MATTER EXPERIMENT

Naive estimate gives
$d_n \approx 10^{-16}$ e-cm





The CP Problem of Strong Interactions

Characterizes degenerate QCD ground state (Θ vacuum)

Phase of Quark Mass Matrix

Standard QCD Lagrangian contains a CP violating term

$$L_{CP} = -\frac{\alpha_s}{8\pi} \underbrace{(\Theta - \arg\det M_q)}_{0 \le \overline{\Theta} \le 2\pi} \mathrm{Tr}\,\tilde{G}_{\mu\nu} G^{\mu\nu}$$

Induces a neutron electric dipole moment (EDM) much in excess of experimental limits

$$d_n \approx \overline{\Theta}\, 10^{-16}\, e\,\mathrm{cm} \approx \frac{\overline{\Theta}}{10^2} \mu_n < 3 \times 10^{-26}\, e\,\mathrm{cm}$$

$\overline{\Theta} \lesssim 10^{-10}$ **Why so small?**

Slide from G. Raffelt

The 1977 Peccei-Quinn solution to the strong-CP problem

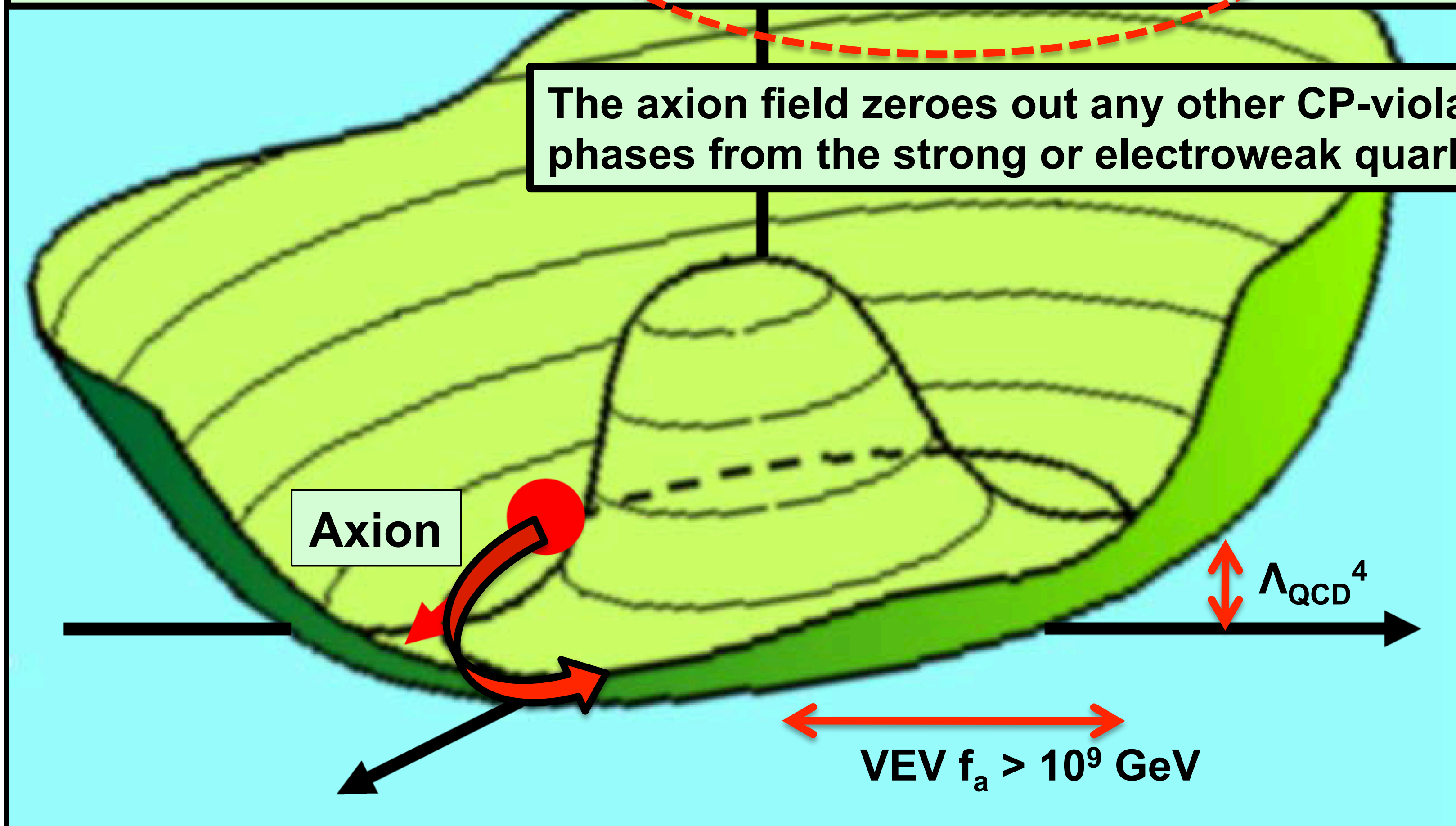
Dirac Medal (2000)

- Postulate a new dynamical scalar field which has a two-gluon coupling.
- Think like an electrical engineer: Use this field in a cosmological feedback loop to dynamically zero out any pre-existing CP-violating phase angles.

Natural potential energy function

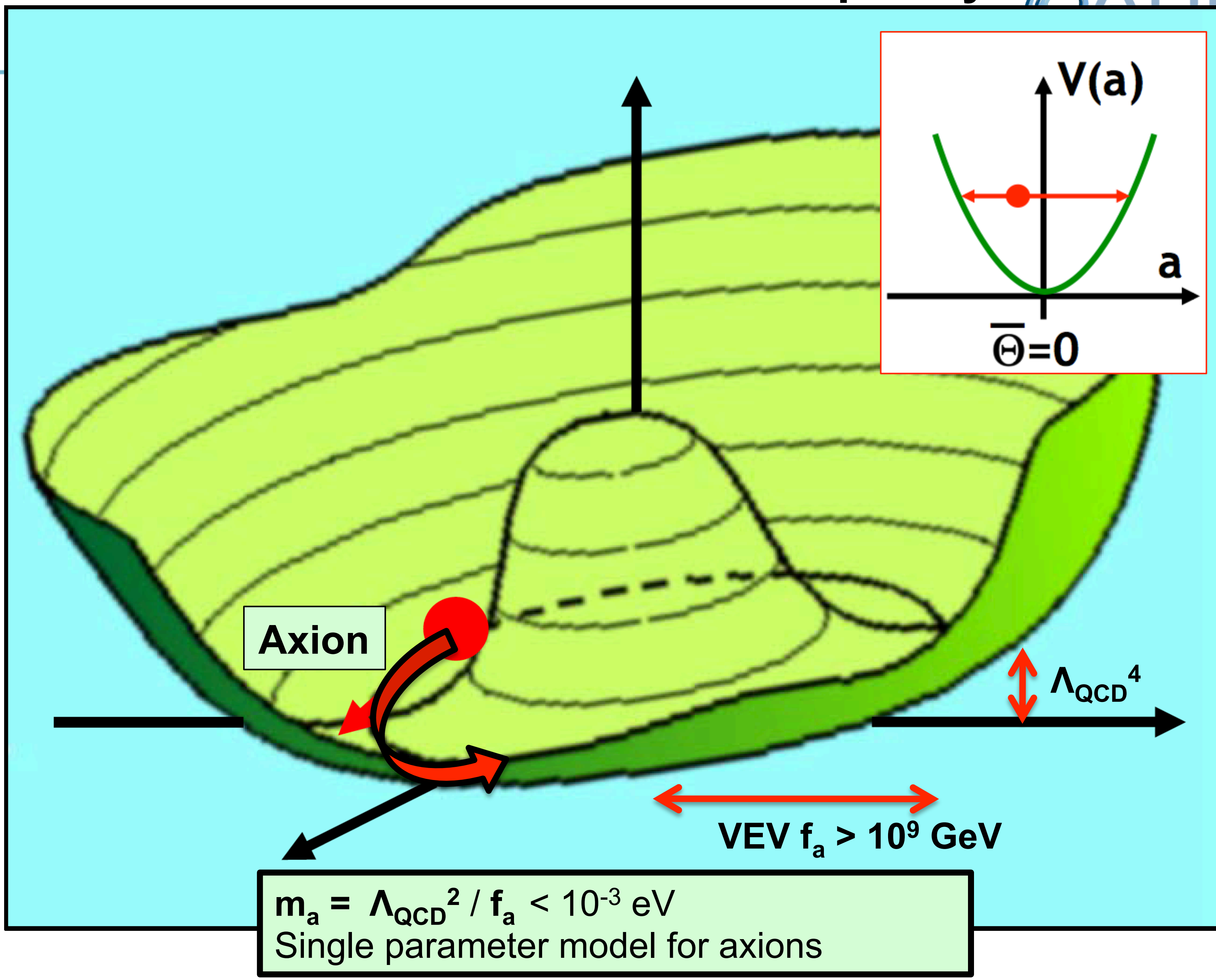
$$V(A) = -f_a^2 A^2 + \frac{\lambda}{4!} A^4 + \left(\frac{g^2}{32\pi^2} \arg(A) - \frac{\alpha_s}{8\pi} \left(\theta_{QCD} + \theta_{quark} \right) \right) \langle G\tilde{G} \rangle$$

The axion field zeroes out any other CP-violating phases from the strong or electroweak quark sector.



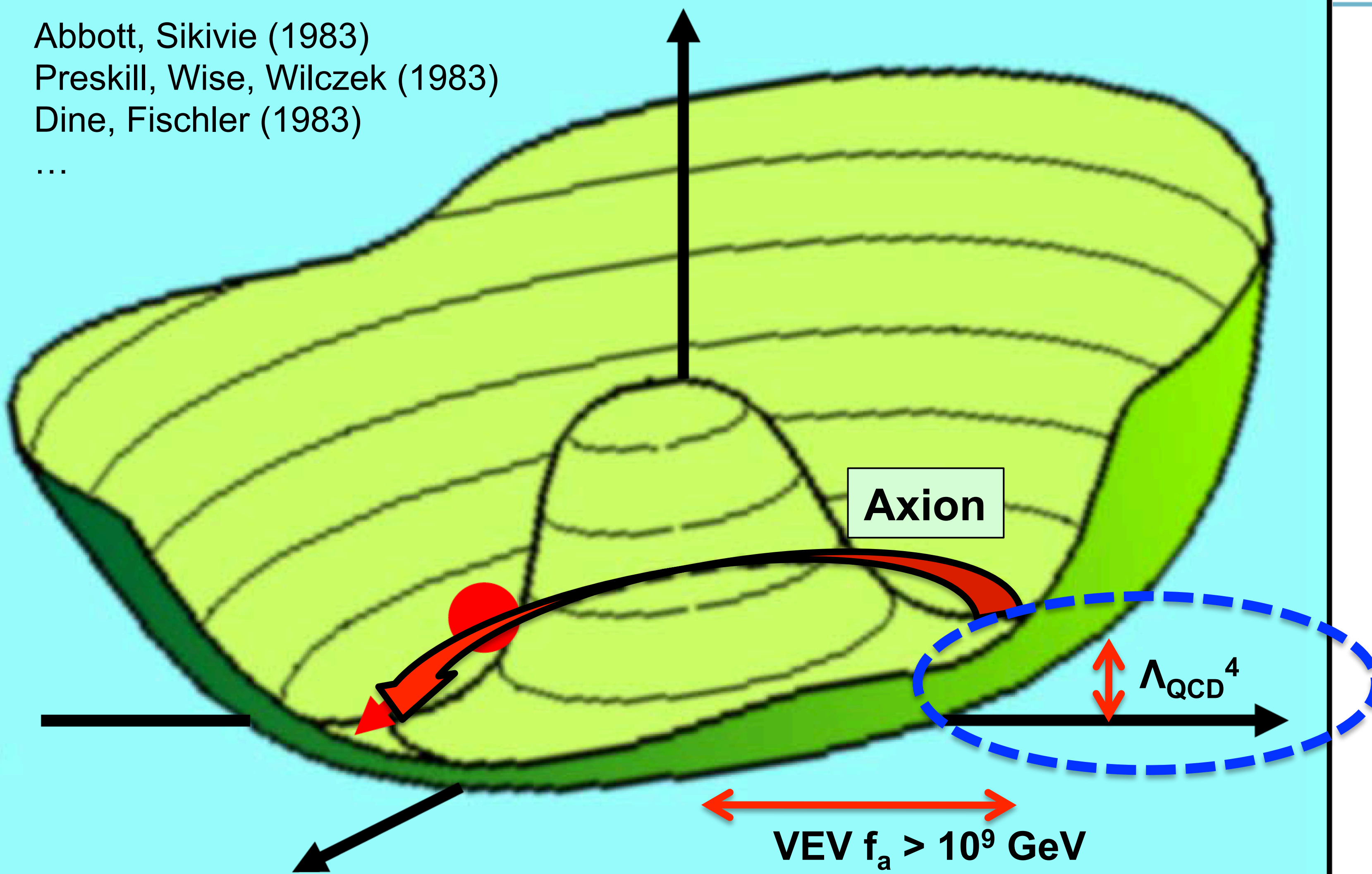
The neutron EDM vanishes, solving the **strong CP fine-tuning problem**.

Axion mass = harmonic oscillator frequency



The initial potential energy density is released as ultracold dark matter

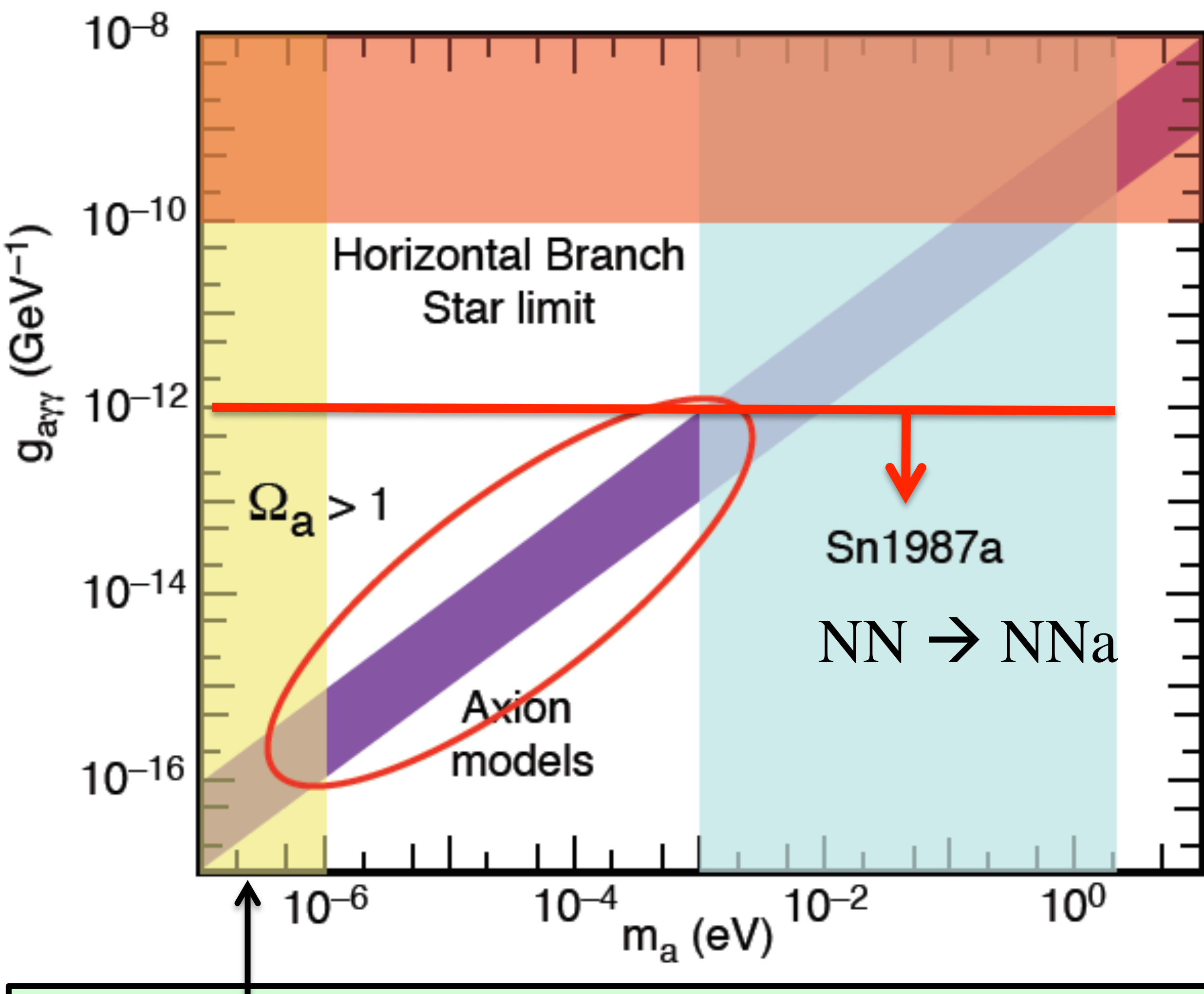
Abbott, Sikivie (1983)
Preskill, Wise, Wilczek (1983)
Dine, Fischler (1983)
…



The initial axial **theta angle θ**, determines the available potential energy to be released. **O(1)×Λ_{QCD}^4** of potential energy density is converted into **dark matter**.

Dark matter is the smoking gun for the PQ model

ADMX AXION DARK MATTER EXPERIMENT



$$\Omega_a \approx \left(\frac{6\,\mu\mathrm{eV}}{m_a}\right)^{\frac{7}{6}}$$

or even more due to cosmic string decay.

PQ model + local energy conservation **guarantees** the existence of dark matter axions in the last place we haven't looked!

Excluded by "naturalness." Requires small initial θ to avoid DM overproduction.

Dark matter axions are spatially and temporally coherent

AXION DARK MATTER EXPERIMENT

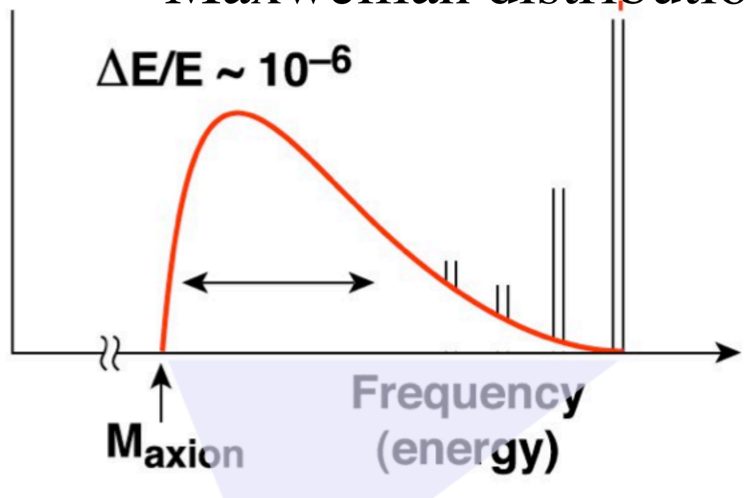
Non-relativistic:

Kinetic energy = $\frac{1}{2} m_a v^2$
$\Delta E = m_a v \Delta v$
$E_{rest} = m_a c^2$

$\Delta E/E = v \Delta v / c^2 \sim 10^{-6}$

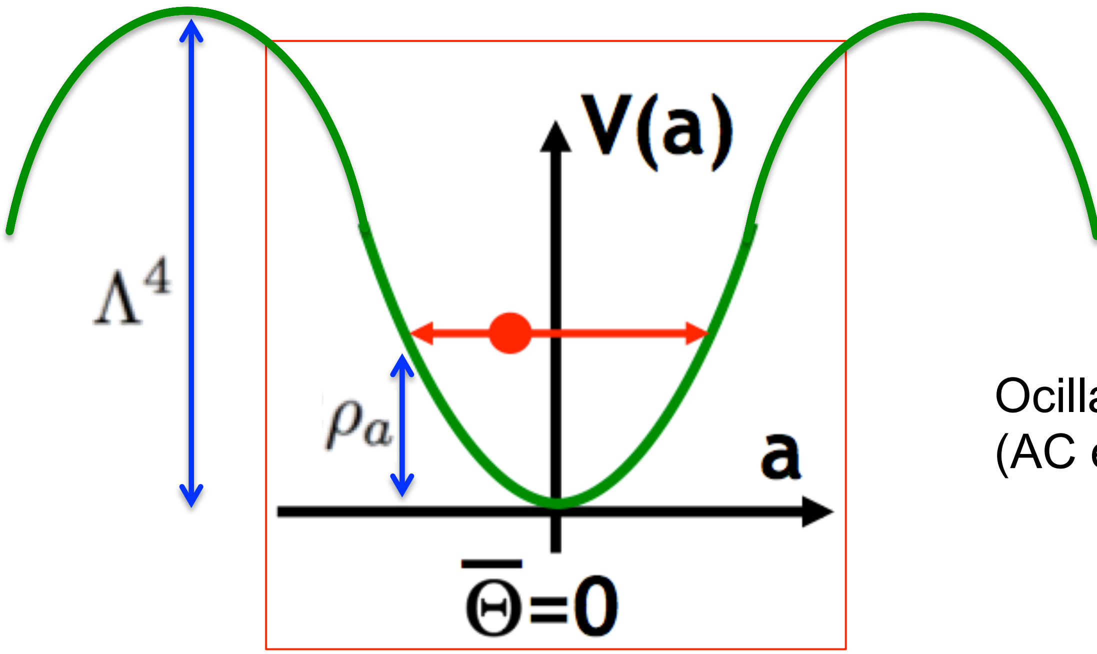
Accidental coherence time:
$\Delta t = 1/\Delta E$
$\sim 10^6$ oscillation periods

Maxwellian distribution



kHz linewidth similar to that of a modern solid state laser

Axion DM induces a coherent oscillation of θ angle about its CP-conserving minimum

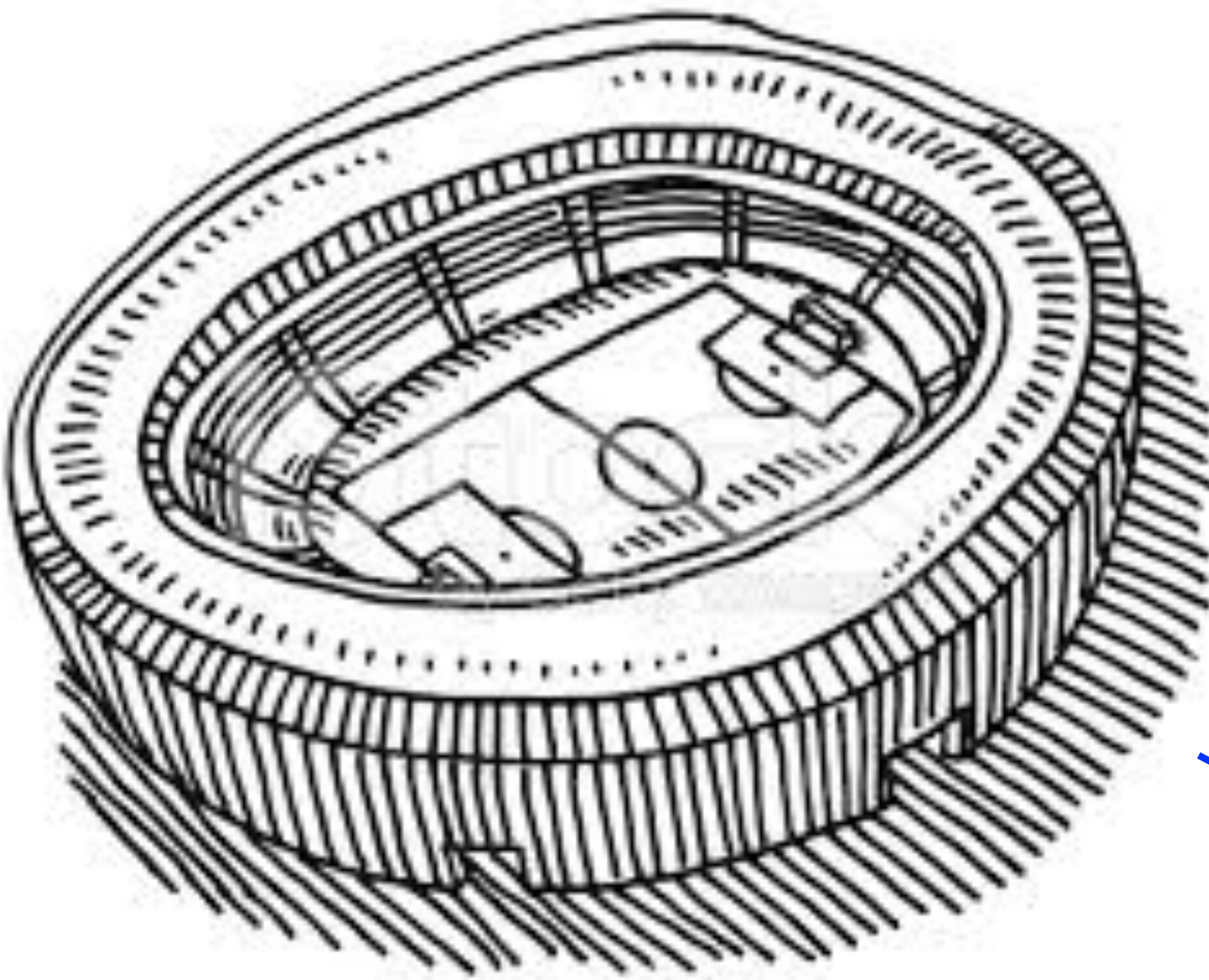


Ocillating θ rotates B→E, m→d
(AC electric dipole moment)

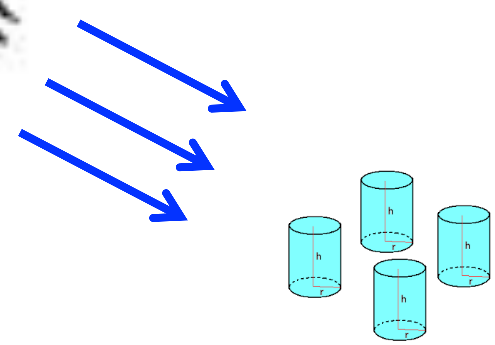
$$\theta(x,t) = \sqrt{2\langle\Delta\theta^2\rangle}e^{i(kx-m_a t)}$$

where $\langle\Delta\theta^2\rangle = 2\rho_a/\Lambda^4$

$$\approx (3.7 \times 10^{-19} \text{ radians})^2$$



300 km/s



Football stadium-sized clumps of coherently oscillating axions drifting through detectors.
Macroscopic occupation number $|\ \alpha = \sqrt{10^{26}\ \text{quanta}}\ \rangle$

→ Phase coherent signals over 10^{-3} s.

Axion DM vs WIMP DM

ADMX
AXION DARK MATTER EXPERIMENT

Low mass bosonic axions:

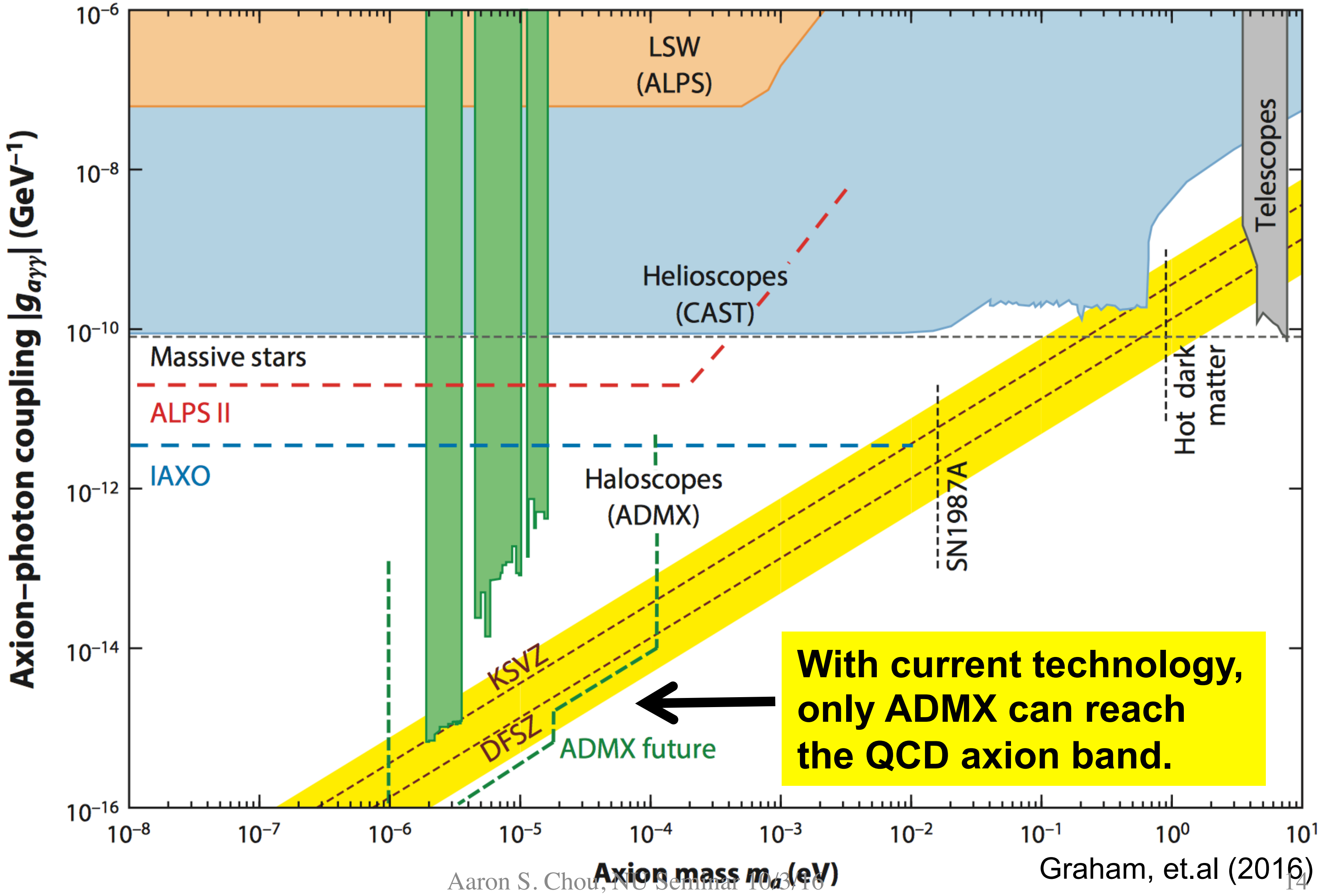
1) Scatter as narrowband classical wave with $N=10^{17}$/liter
2) **Rate suppressed by QCD scale → integration time = minutes**
3) Quantum-limited noise due to measurement back-reaction

Fermionic WIMPs:

1) Scatter as individual quanta, N=1/liter
2) Rate suppressed by electroweak scale → integration time = year(s)
3) Radiogenic backgrounds

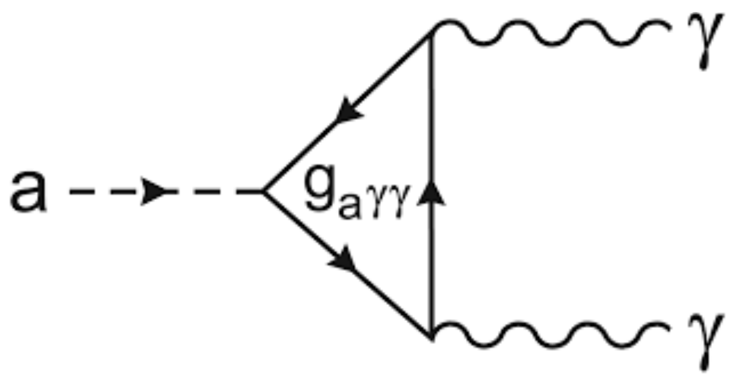
Light-shining-through-walls, Helioscopes have signal rates suppressed by $f_a >> \Lambda_{QCD}$

and are only sensitive to more strongly-coupled "axion-like" particles



Graham, et.al (2016)

Detect via induced axion-photon coupling



In the presence of a strong background magnetic field B_0 :

$$\mathcal{L}_{\rm int} = g_\gamma \theta \vec{B}_0 \cdot \vec{E}$$

$$= \underbrace{g_\gamma \partial_t \theta \vec{B}_0}_{\vec{J}_a(t)} \cdot \vec{A} \quad + \ldots$$

The oscillating dark matter axion field acts as an exotic, space-filling current source:

$$\vec{J}_a(t) = -\frac{g\alpha}{\pi}\left(\frac{\sqrt{2\rho_a}}{\Lambda^2_{\rm QCD}}\right)\vec{B}_0 m_a e^{i m_a t}$$

The Sikivie Haloscope technique (1983)

- In a constant background B_0 field, the oscillating axion field acts as an exotic, space-filling current source

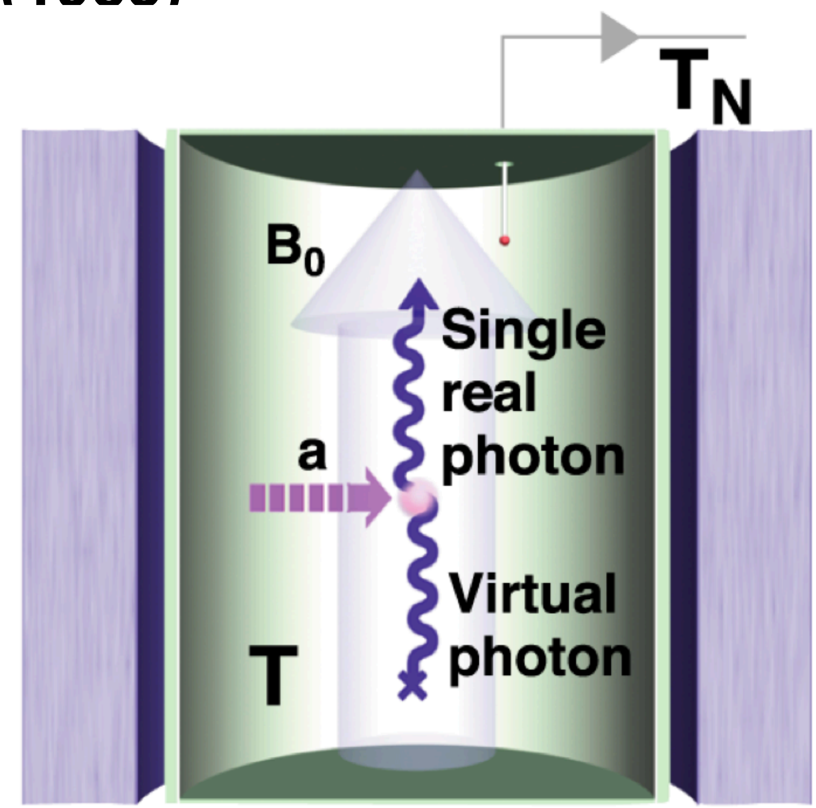
$$\vec{J}_a(t) = -\frac{g\alpha}{\pi}\left(\frac{\sqrt{2\rho_a}}{\Lambda^2_{\mathrm{QCD}}}\right)\vec{B}_0 m_a e^{i m_a t}$$

which couples to EM via Faraday's law:

$$\vec{\nabla} \times \vec{B}_r - \frac{d\vec{E}_r}{dt} = \vec{J}_a$$

- In the presence of matched cavity boundary conditions to absorb momentum, the exotic source current excites standing-wave RF photons.

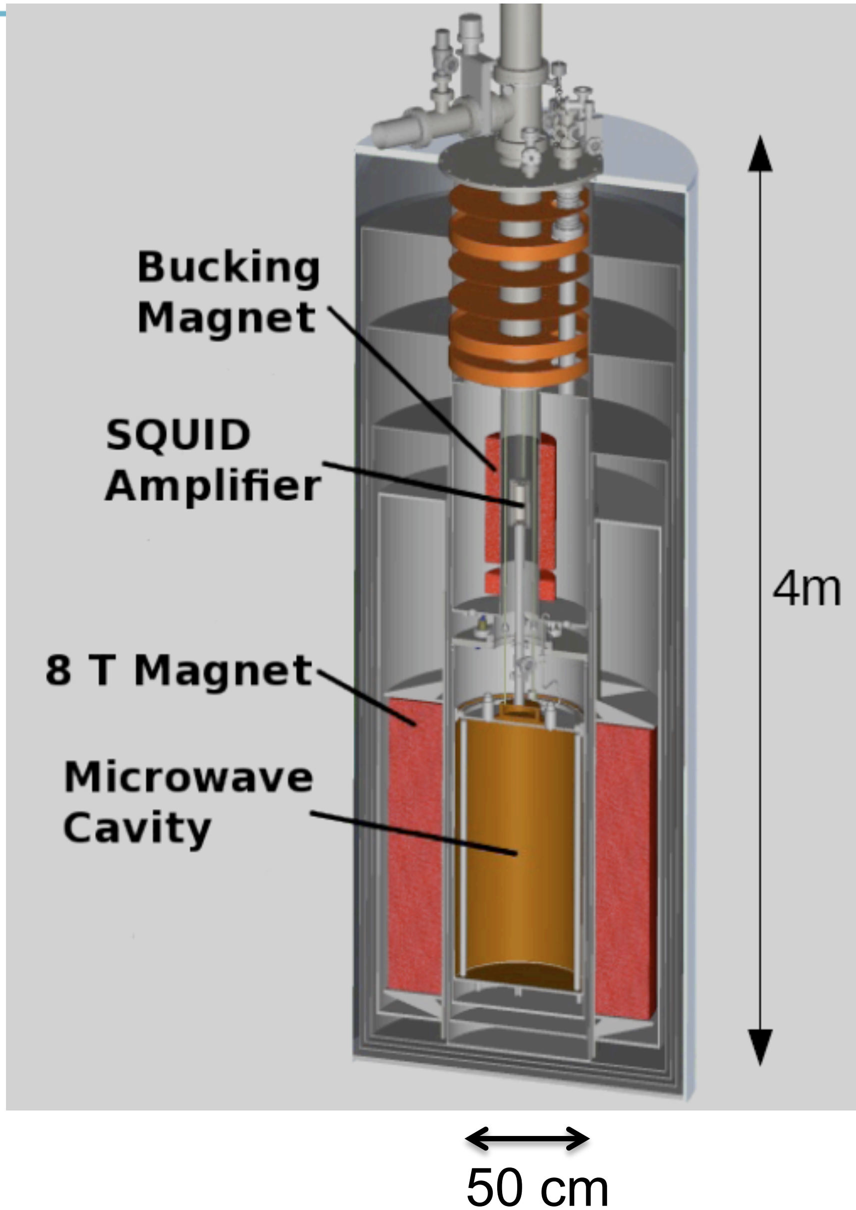
- **RF photon frequency = axion mass**
  - Classic window range: 250 MHz – 250 GHz



The Haloscope **optimally** extracts power from the potential energy of interaction:

$$P_a(t) = \int \vec{J}_a(t) \cdot \vec{E}_r(t)\, dV$$

ADMX Generation 2 Project located at U.Washington



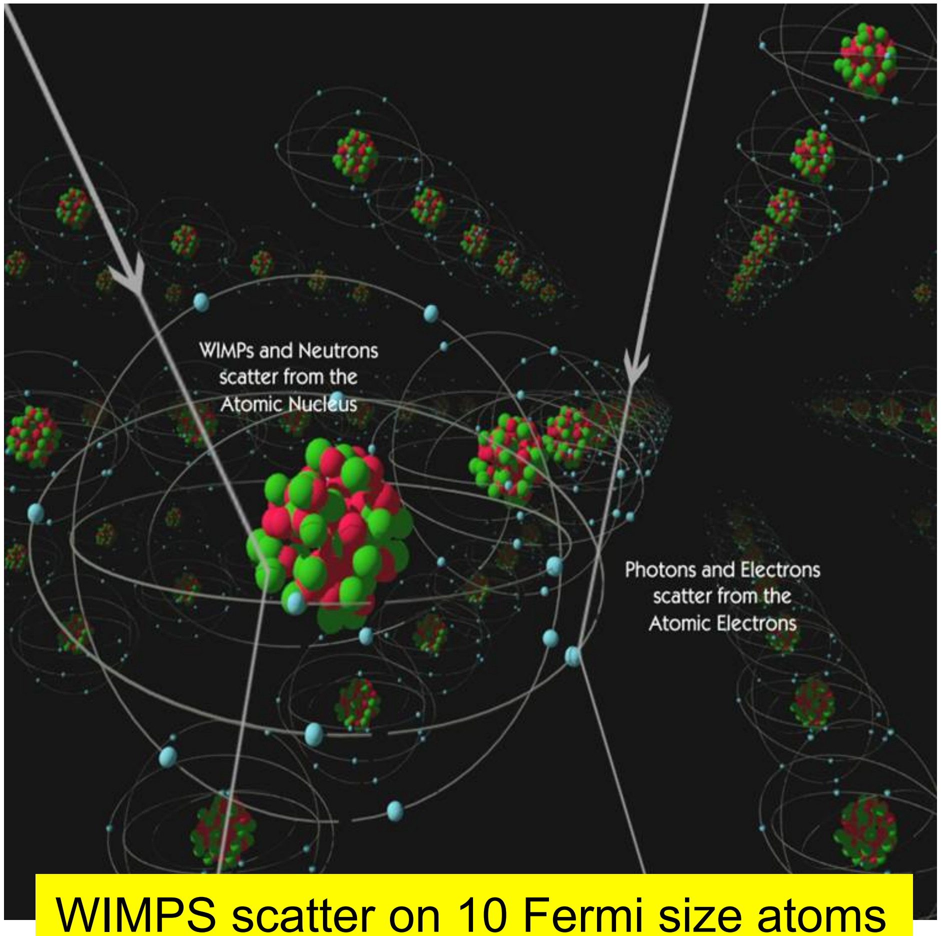
Cryogenic operation is necessary to suppress thermal blackbody noise down to the quantum limit.

Axions vs WIMPs:

ADMX AXION DARK MATTER EXPERIMENT

Resonant scattering requires size of scattering target = 1/(momentum transfer)

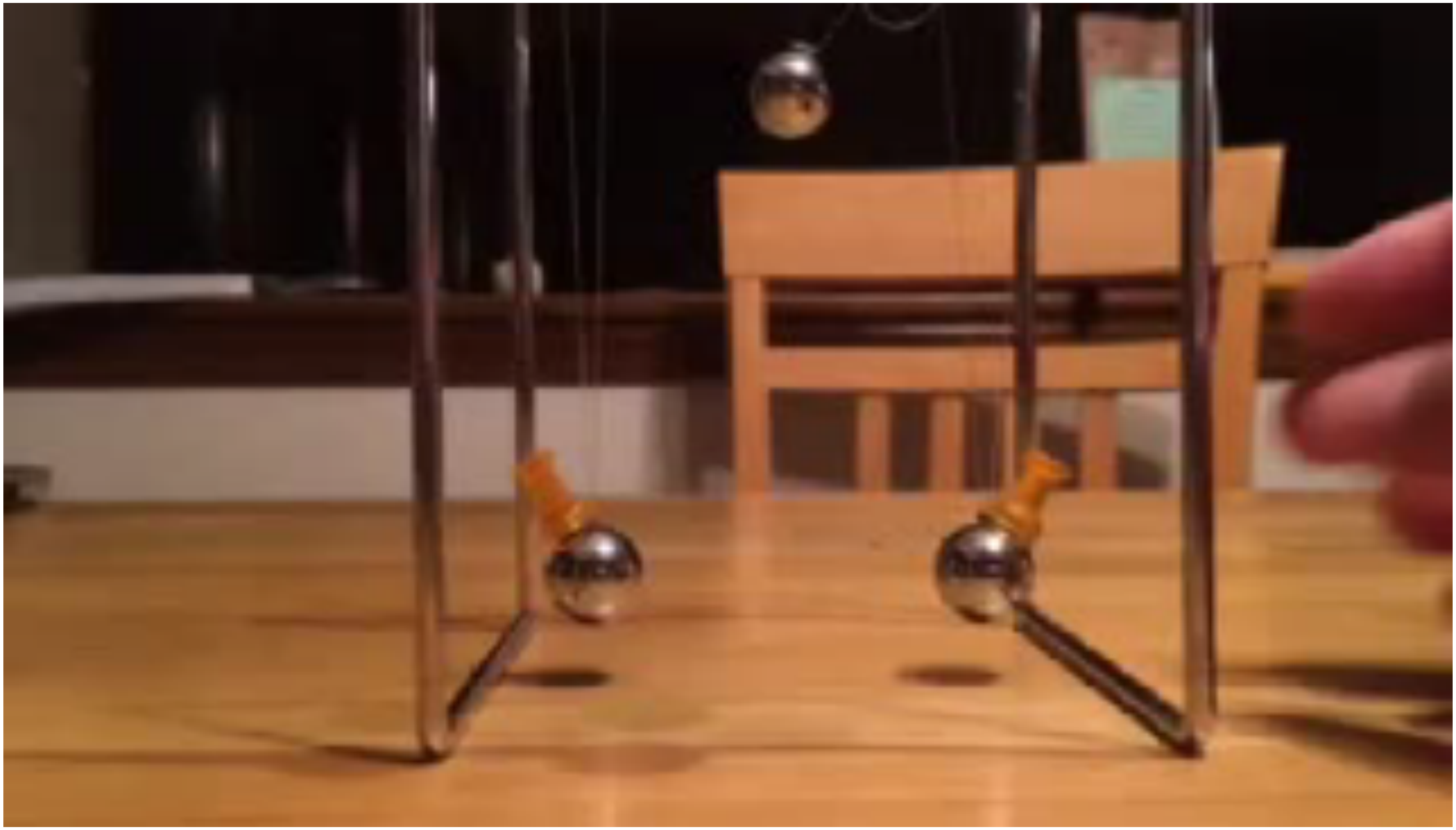
4 μeV mass axions scatter on 50cm size microwave cavities



WIMPS scatter on 10 Fermi size atoms

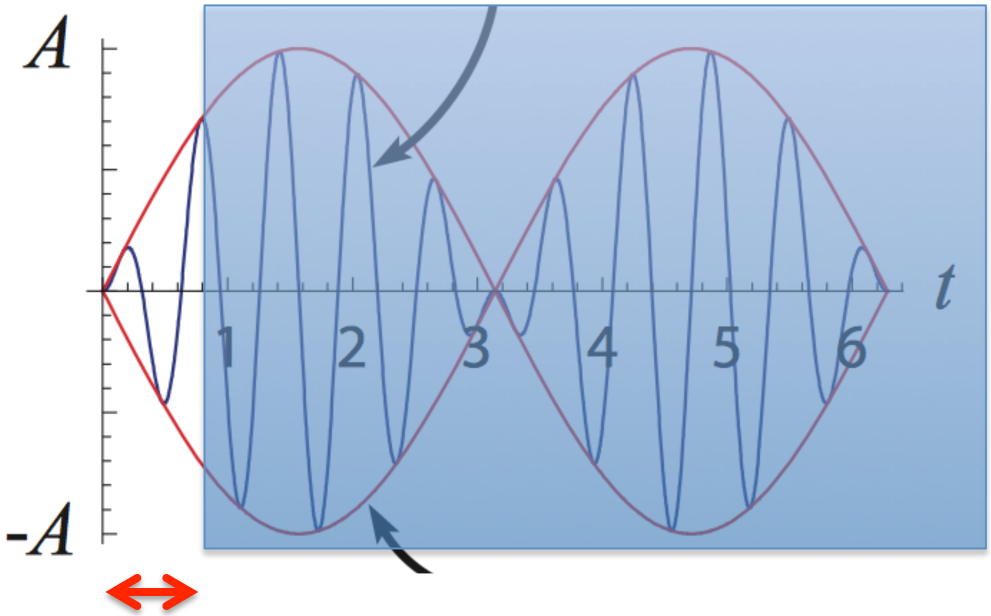
Higher frequency axion searches will require many smaller cavities.

Power transfer increased by time coherence between cavity E field and axion field



Weak coupling -- takes many swings to fully transfer the wave amplitude.
Number of swings = cavity Quality factor.
Narrowband cavity response → iterative scan through frequency space.

The quality factor Q_{cav} determines the cavity coherence time t_{cav} over which the axion signal can be coherently accumulated as cavity E field



$t_{cav} = 1/df_{cav} = Q_{cav}/f$

Oscillation period = 1/(Interaction Energy)

>> coherence time

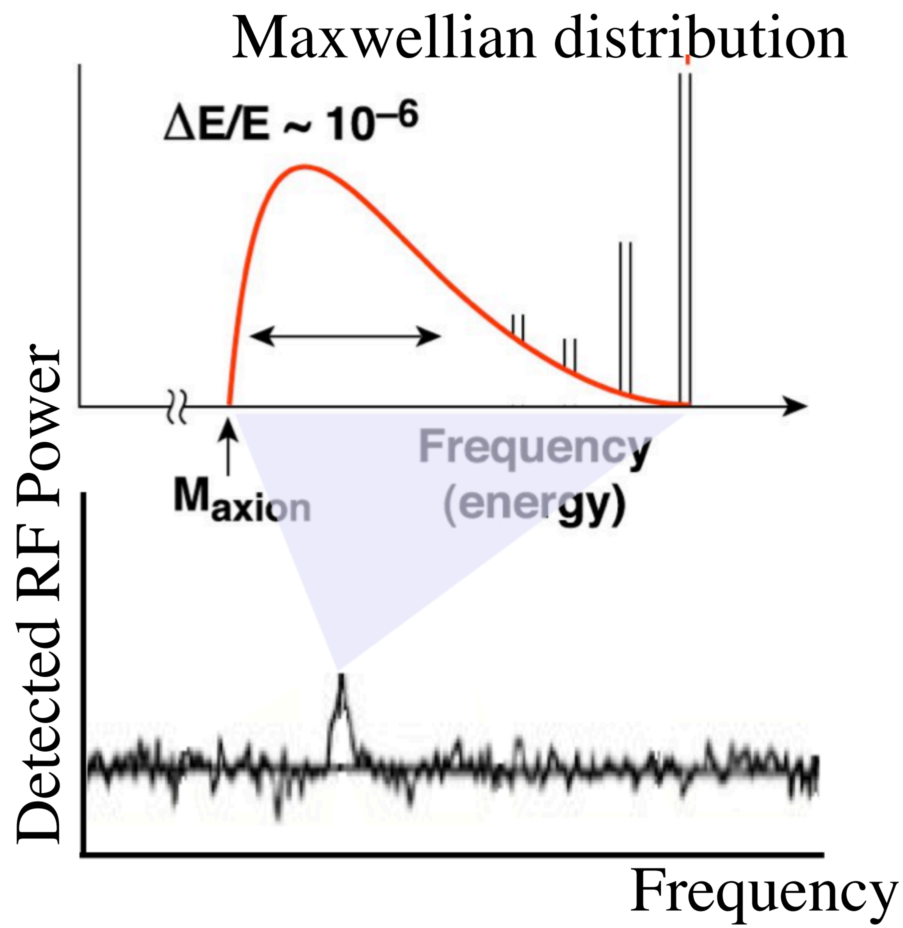
Square the wavefunction → **the accumulated energy scales as $(t_{cav})^2 = Q_{cav}^2 / f^2$**

Axion line is kinetically broadened

Non-relativistic:

Kinetic energy = ½ m_a v^2
$\Delta E = m_a\, v\, \Delta v$
$E_{rest} = m_a\, c^2$

$\Delta E/E = v\, \Delta v / c^2 \sim 10^{-6}$

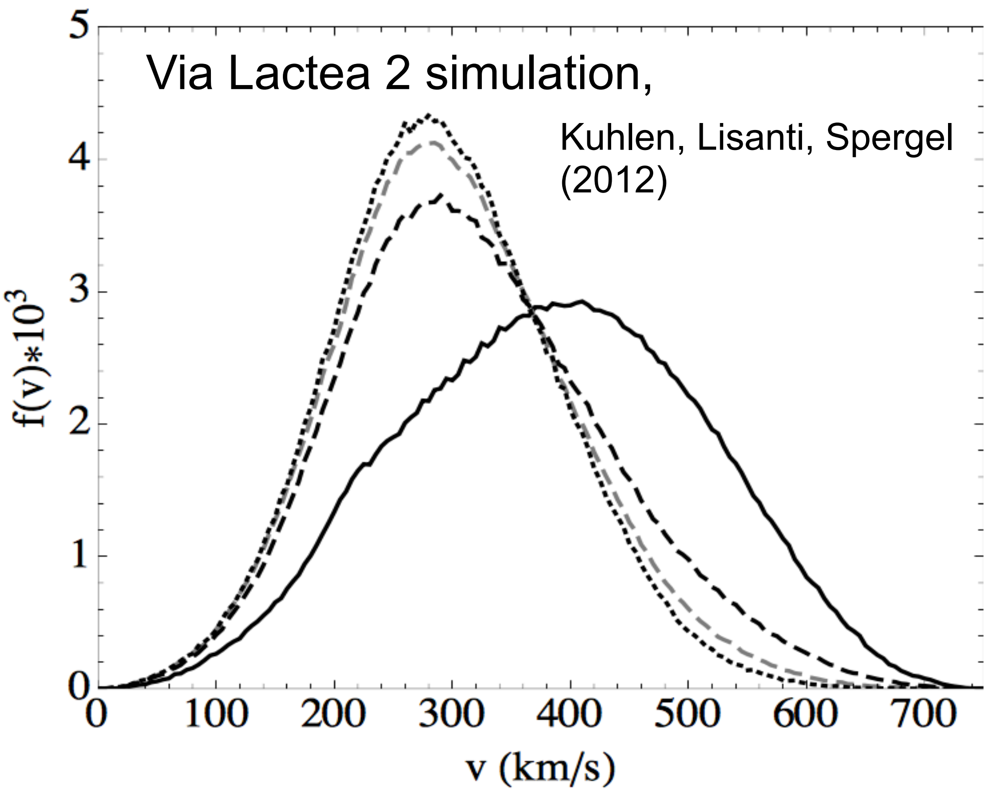


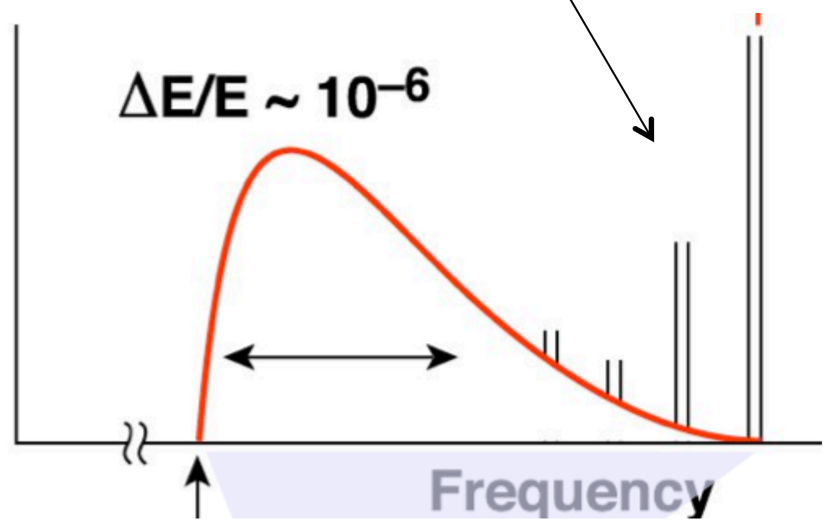
Very narrowband line, but can reconfirm signal in minutes once found.

Like J/Ψ scan: most of search time spent slowly stepping through frequency space, one cavity tuning at a time.

Can obtain axion phase space distribution immediately after discovery + reconfirmation

Search for structure due to recent infalls, galaxy mergers, etc.

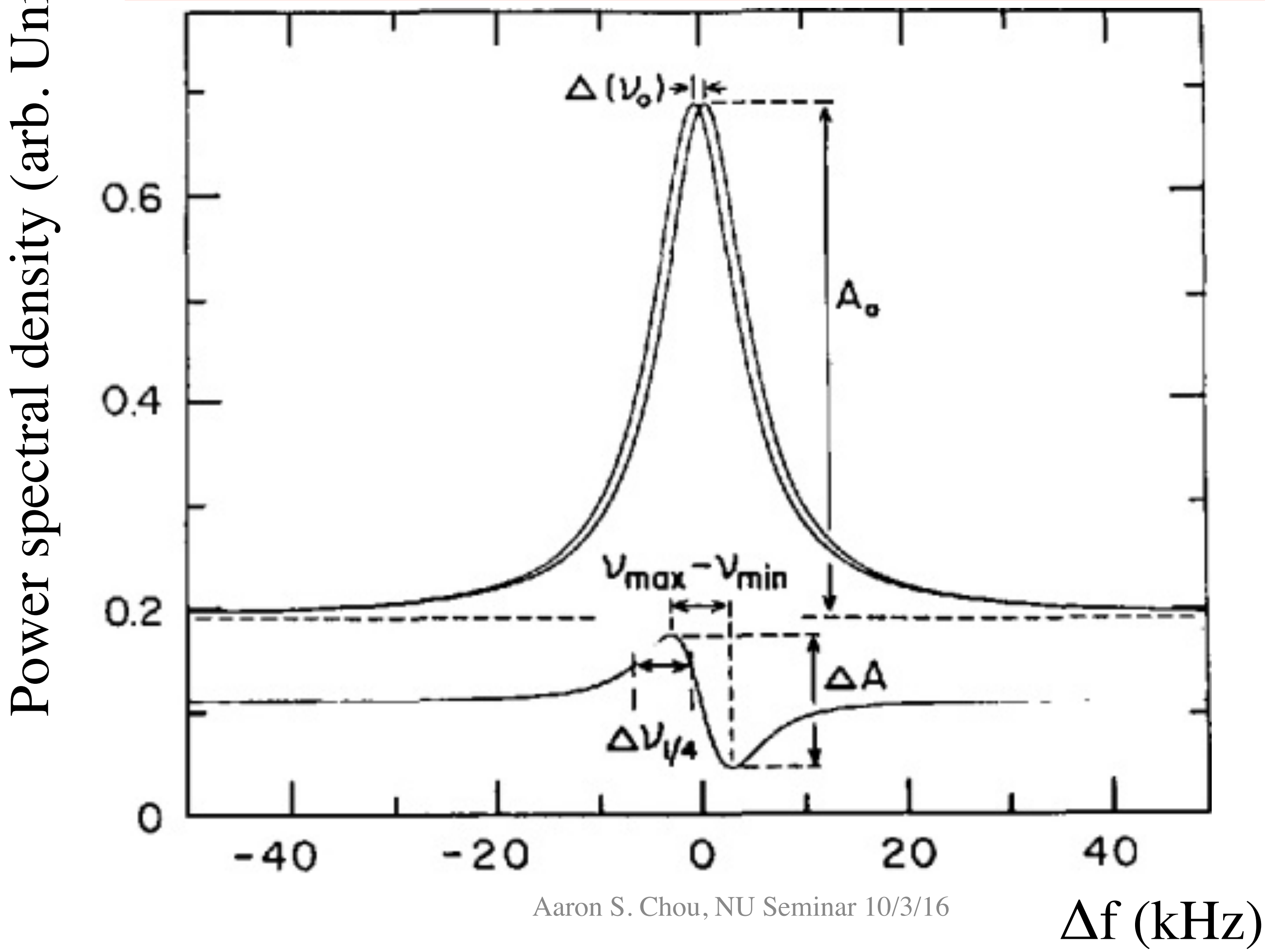




For 2x frequency resolution, need 2x sample time. Half-power in each bin requires 4x samples. Total 8x integration time is easy!

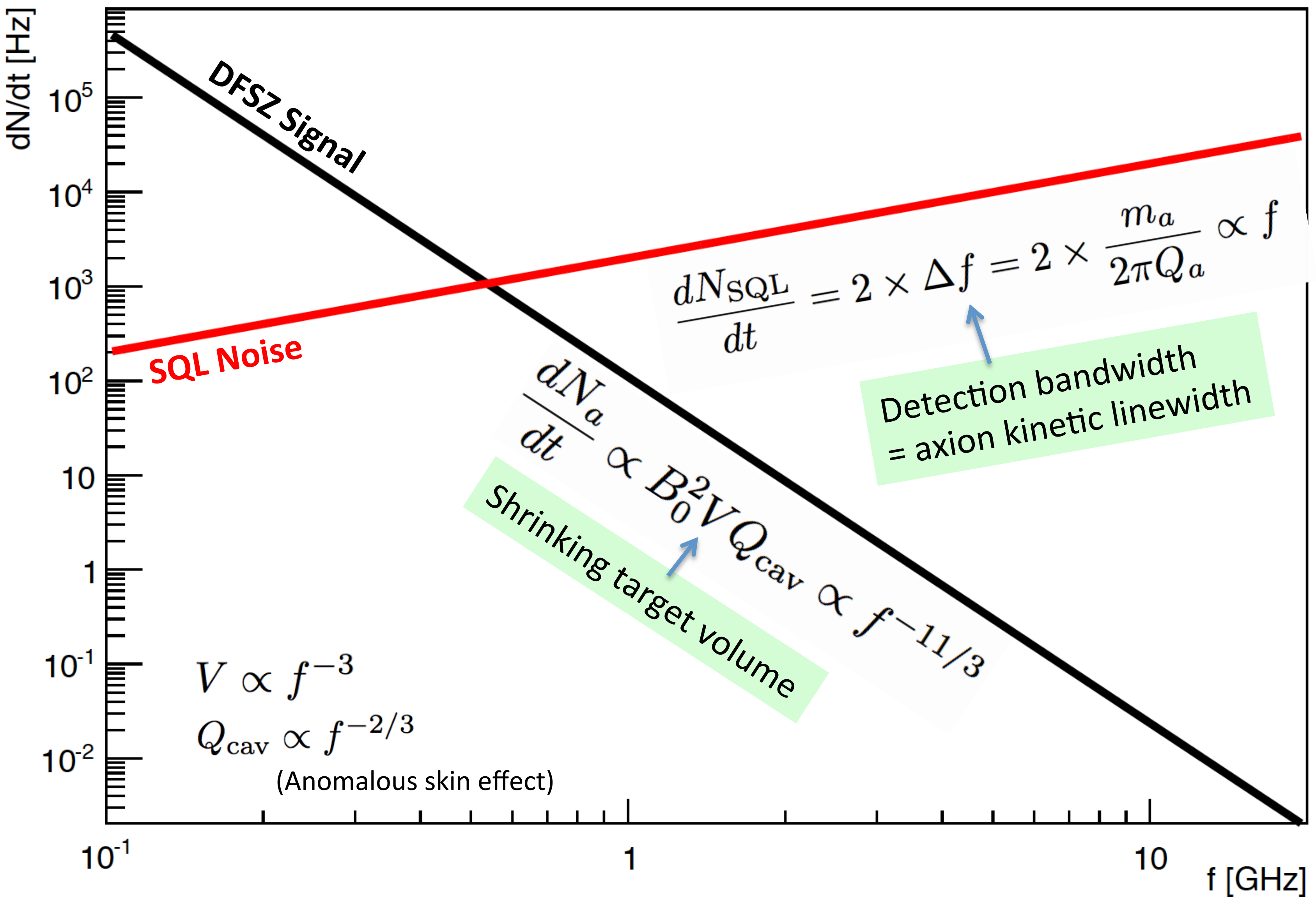
Annual modulation is also easy

Annual modulation δv/Δv = (60 km/s) / (300 km/s) = 20% of linewidth.
Resolve frequency shift with 5x integration time = few 10's minutes.

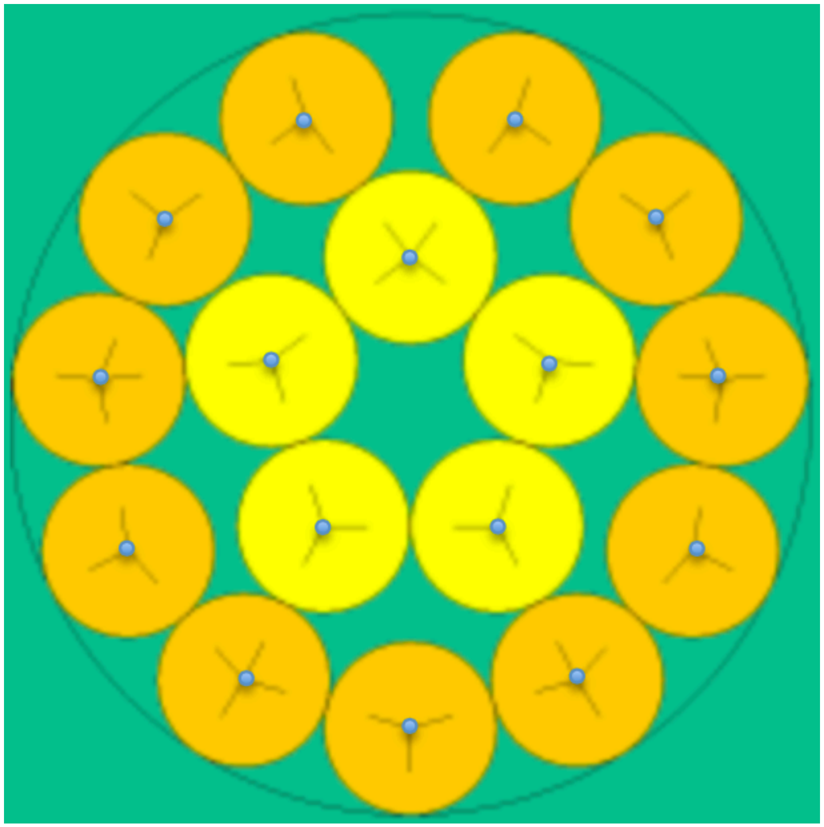


What are the experimental challenges?

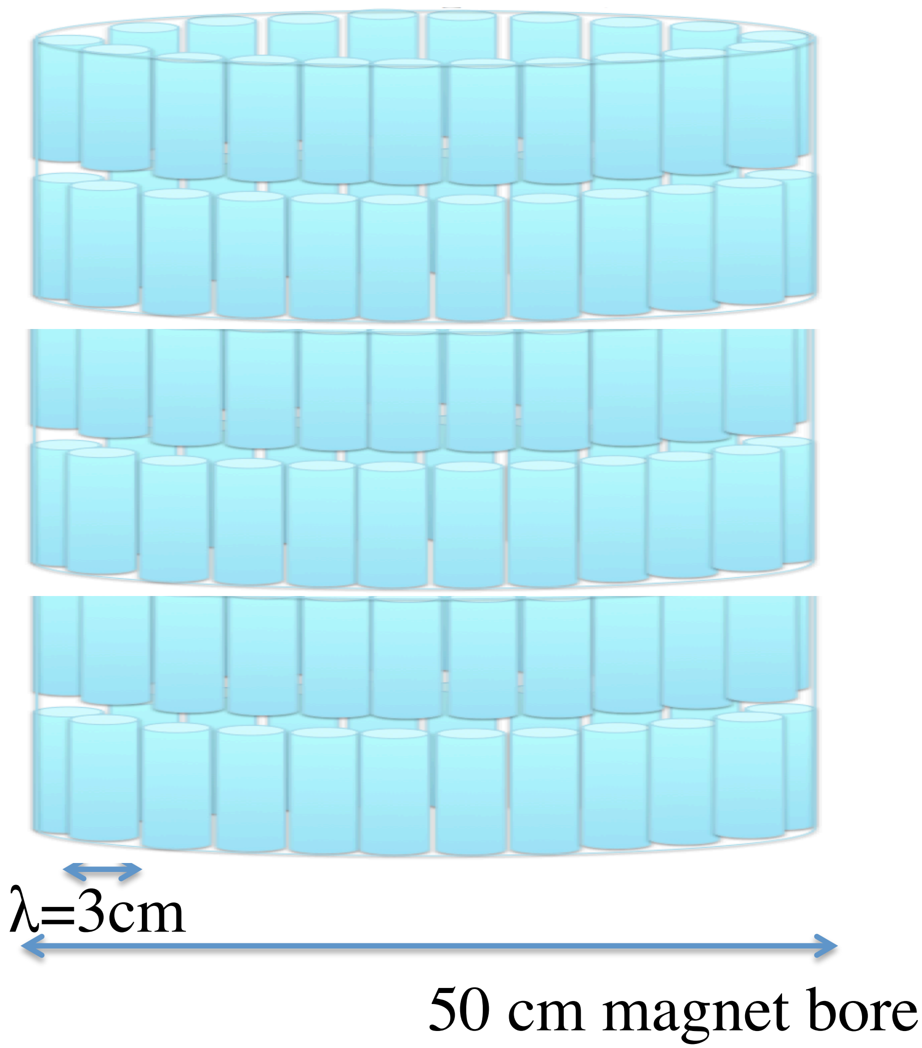
DFSZ axion signal photon rate for single volume=λ^3 cavity vs. **Standard Quantum Limit** readout noise



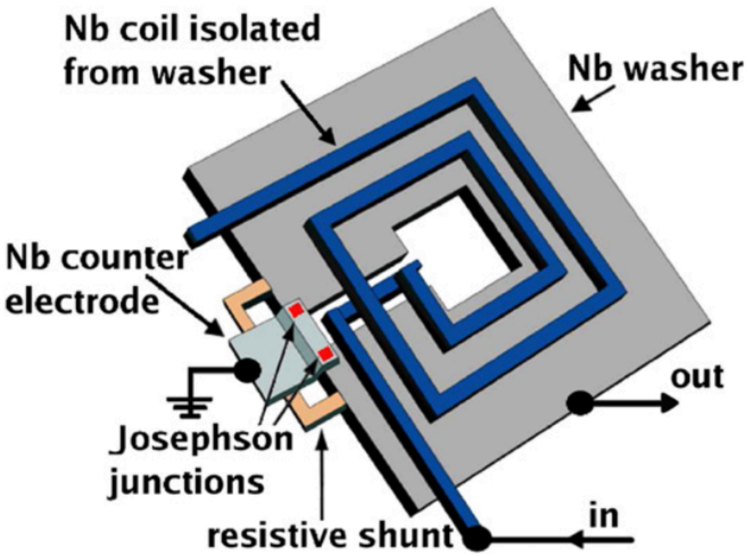
Swiss watch problem: Many resonant elements must be simultaneously tuned to the same frequency

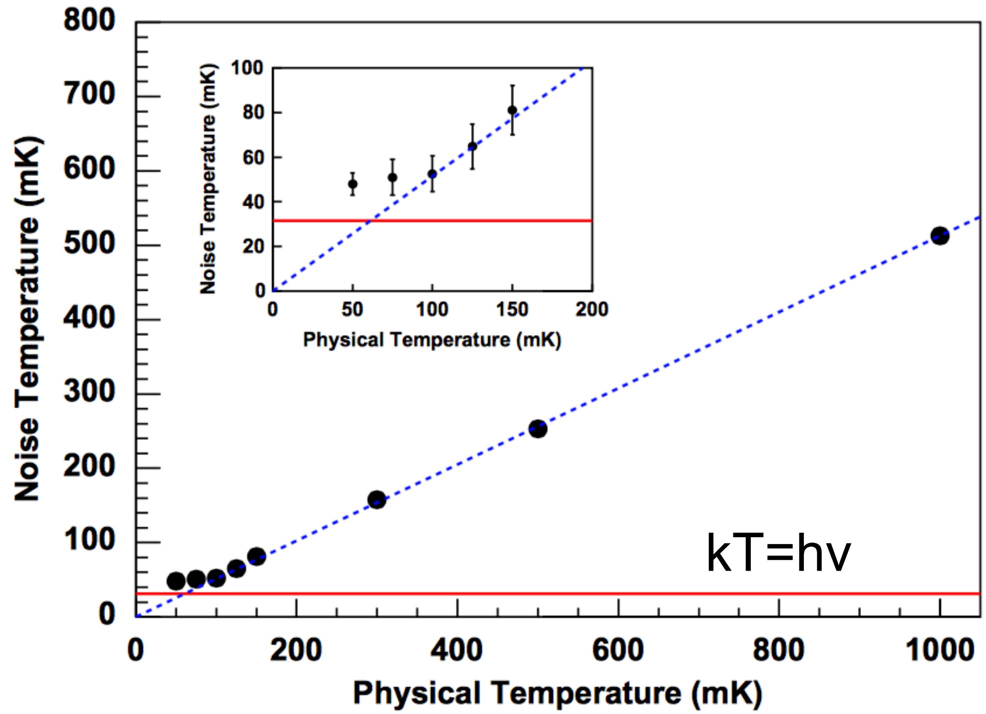


Cost and complexity scale at least linearly with N_{cav}



Quantum-limited amplifiers

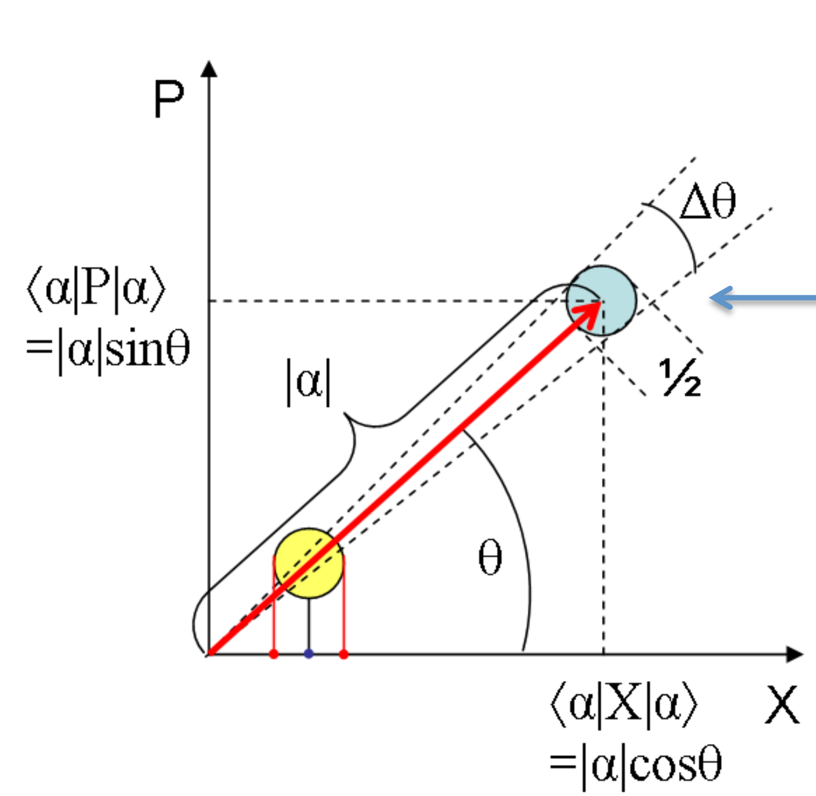




Microstrip Squid Amplifier operates up to 1 GHz.

Josephson Parametric Amplifiers for 1-10 GHz.

Quantum-limited amplifiers suffer from zero-point readout noise – the Standard Quantum Limit (SQL)



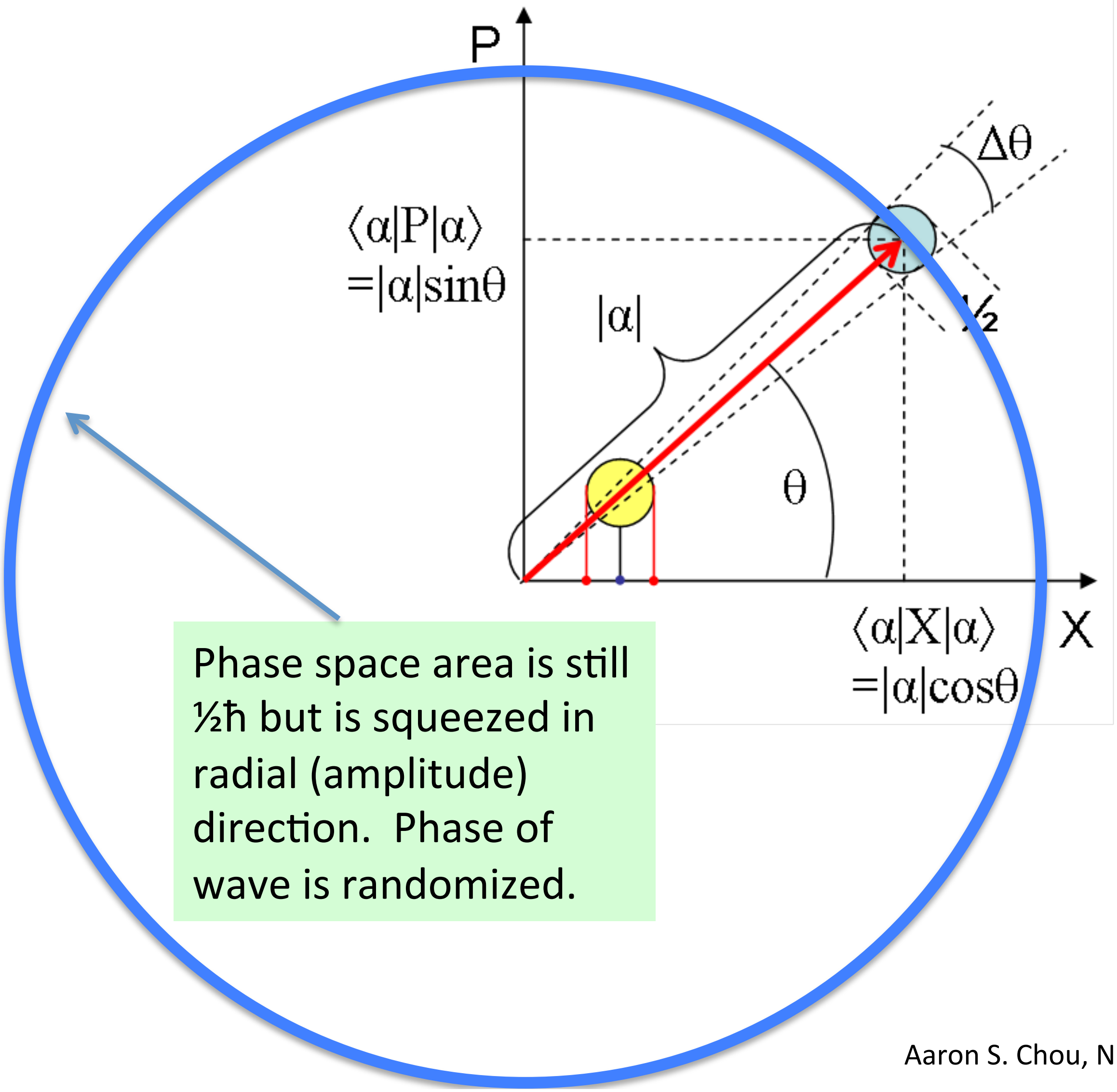
½ ħ= quantum of phase space area.
Simultaneous measurement of wave amplitude and phase gives irreducible zero-point noise in measurement.
(Caves, 1982)

Thermal noise = kT of energy per resolved mode
→ **Quantum noise = 1 photon per resolved mode in the T=0 limit.**

Noise photon rate exceeds signal rate in high frequency dark matter axion searches.
Need new sensor technology….

Quantum non-demolition (QND) single photon detection can do much better

Number operator commutes with the Hamiltonian→ all backreaction is put into the phase. Measure exact photon number. Noise = shot noise, thermal backgrounds, read noise.



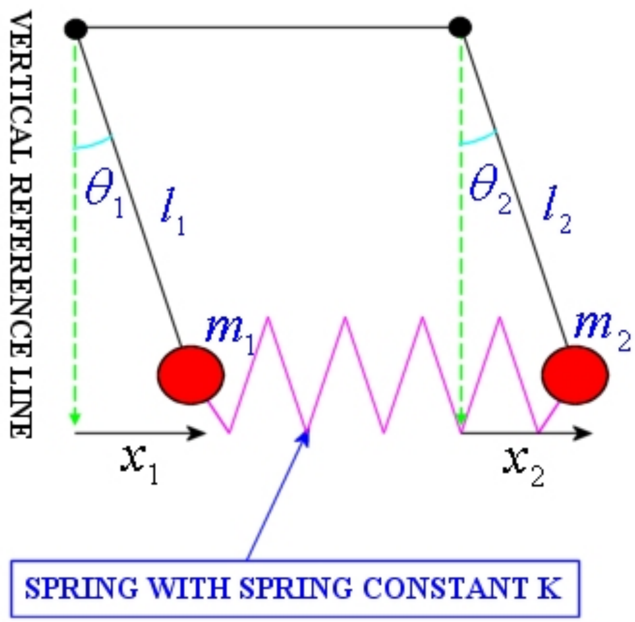
Demonstrated with Rydberg atoms, (Haroche/Wineland Nobel Prize 2012)

Implementation using solid state artificial atom qubits, (D.Schuster et.al, 2007)

Proposed for axion search: (Lamoreaux, et.al, 2013, Zheng, et.al, 2016)

What does a QND single microwave photon detector look like?

Coupled oscillators



Energy stored in the spring

$$H = \begin{pmatrix} \omega_1 & g \\ g & \omega_2 \end{pmatrix}$$

Mixing angle to diagonalize:

$$\tan 2\theta = 2g/(\omega_1 - \omega_2)$$

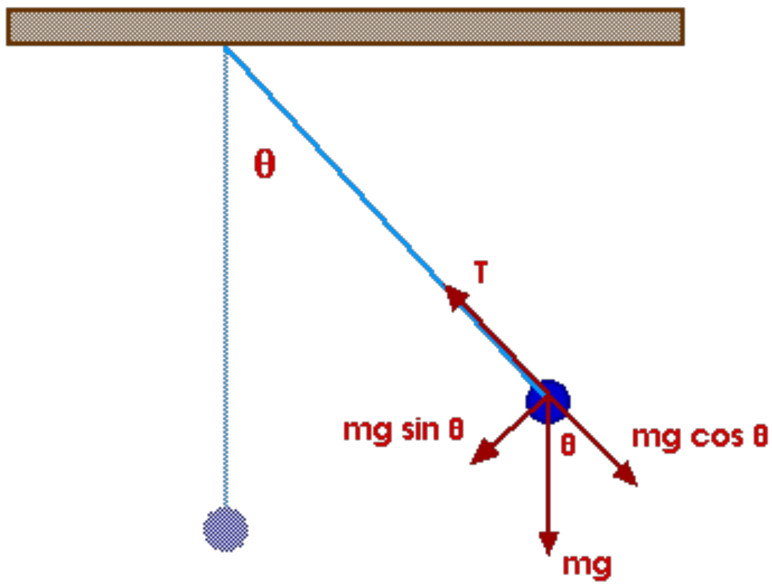
Normal mode frequencies for small g

$$\tilde{\omega}_1 = \omega_1 + \frac{2g^2}{\omega_1 - \omega_2}$$

$$\tilde{\omega}_2 = \omega_2 - \frac{2g^2}{\omega_1 - \omega_2}$$

Pendula talk to each other through the mixing angle.

Suppose one oscillator has non-linear restoring force



For example:
Resonant frequency of a real-world pendulum increases with oscillation amplitude

$\boldsymbol{\omega_2 = \omega_2(A_2)}$

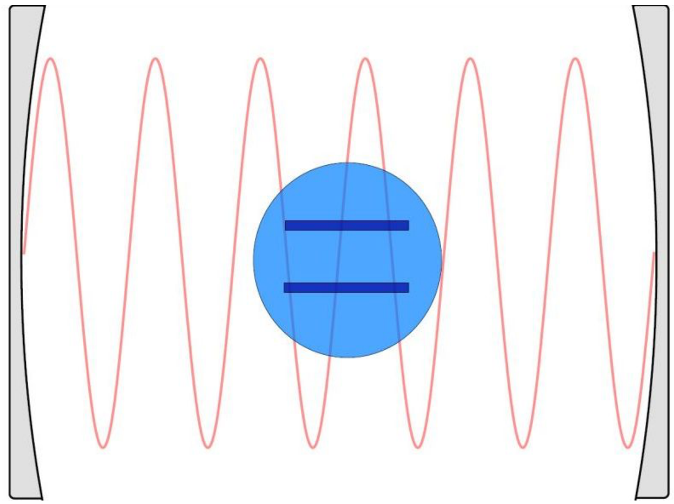
Then the instantaneous resonant frequency of **linear** oscillator 1 depends weakly on the amplitude or occupation number of **nonlinear** oscillator 2

$$\tilde{\omega}_1 = \omega_1 + \frac{2g^2}{\omega_1 - \omega_2(A_2)}$$

Measuring the frequency of oscillator 1 performs a QND measurement on the number of quanta stored in oscillator 2 (and vice-versa)

Cavity QED:
Use 2-level atom to measure cavity photon population

Linear cavity
Bosonic oscillator,
Number operator = $a^\dagger a$



2-level "atom"
Fermionic oscillator,
Number operator = σ_z

The 1st order non-linearity in (number operator)^2 in the undiagonalized Hamiltonian is:

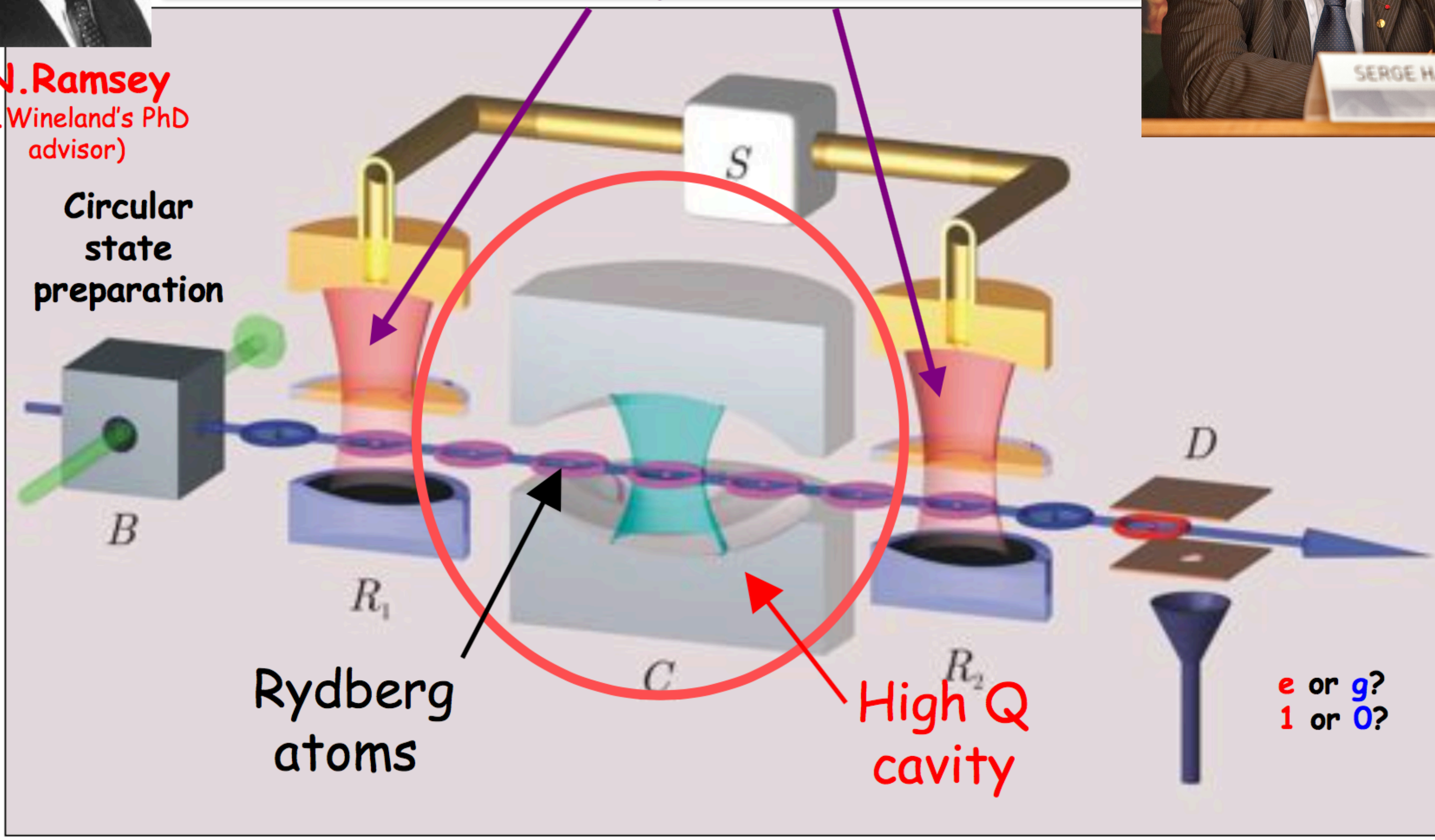
$$H \approx \hbar\omega_r (a^\dagger a + 1/2) + \frac{\hbar}{2}\left(\omega_a + \frac{2g^2}{\Delta} a^\dagger a + \frac{g^2}{\Delta}\right)\sigma_z$$

$\Delta = \omega_r - \omega_a$

The atom frequency depends on the cavity resonator's occupation number!
This product of number operators commutes with H and allows QND measurement.

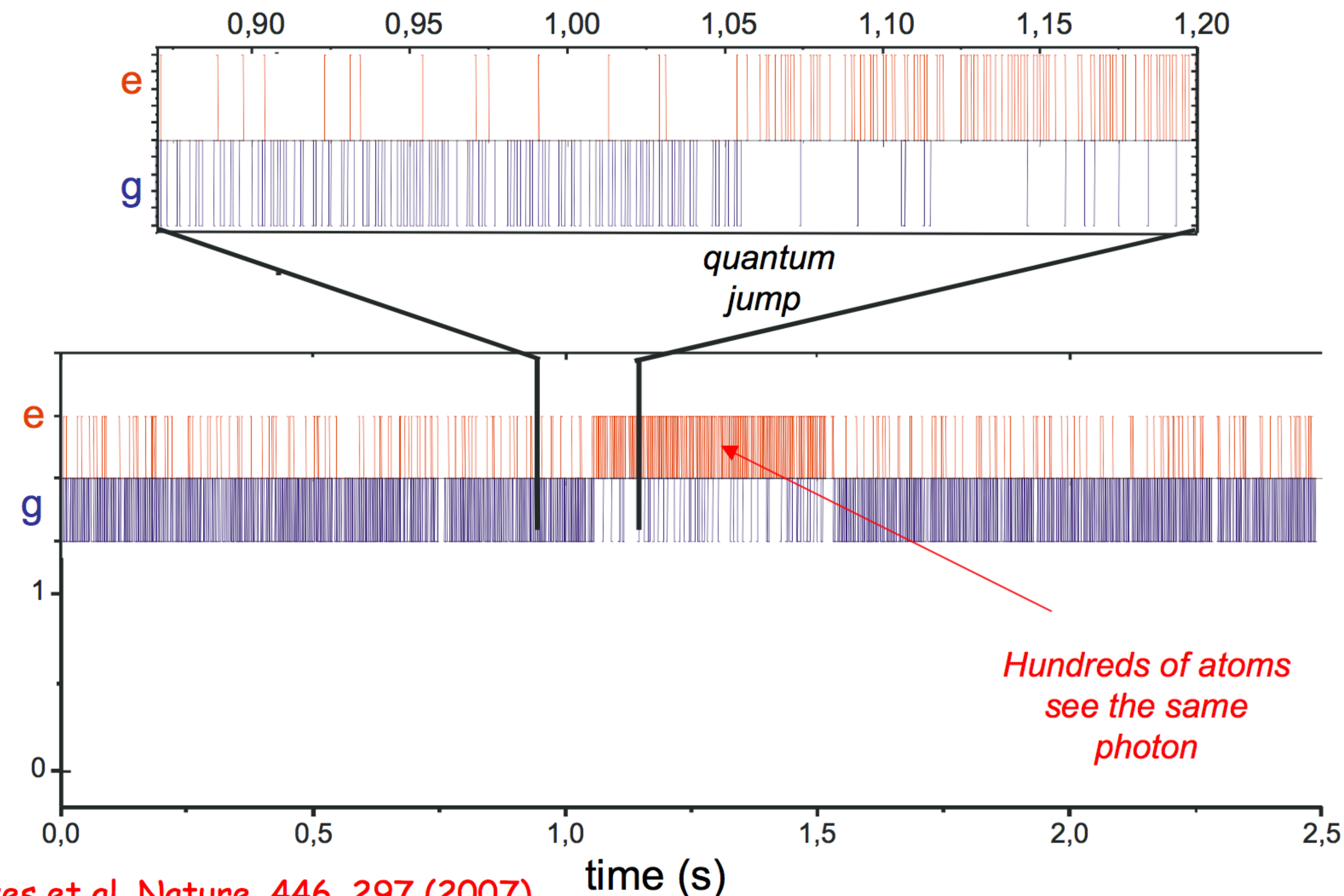
Serge Haroche 2012 Nobel Prize:
Atoms acts an amplitude→ frequency transducers.
They probe the cavity photon number without any net absorption of photons.
Analogous to neutrino "matter effects."

N.Ramsey
(D.Wineland's PhD advisor)



An atomic clock delayed by photons trapped inside

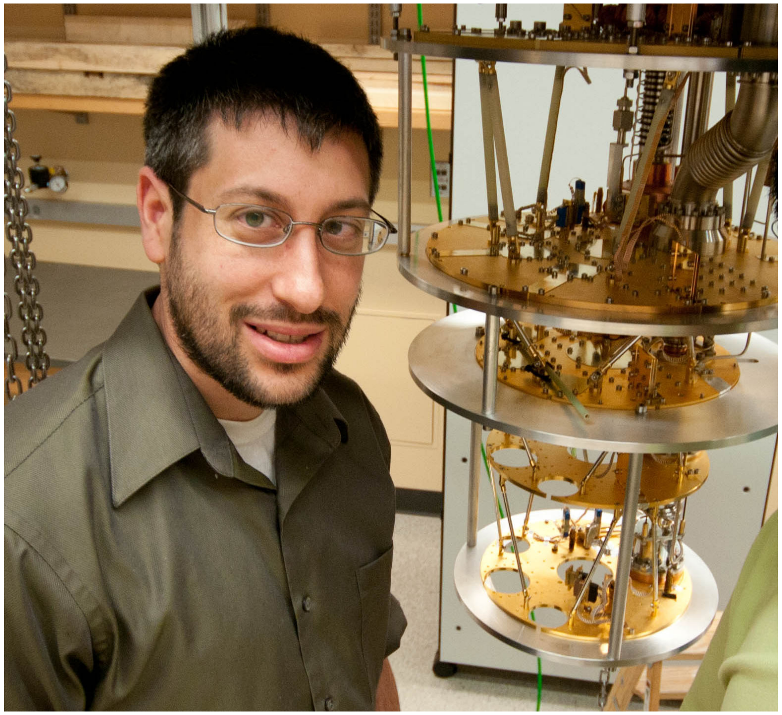
Birth, life and death of a photon



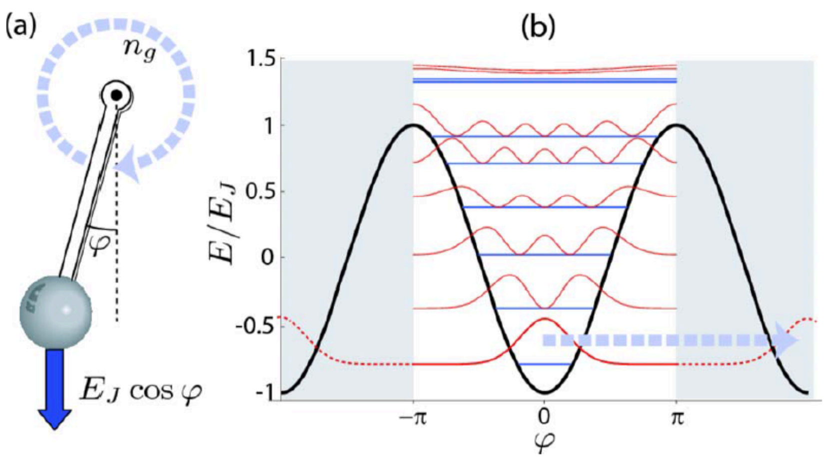
S.Gleyzes et al, Nature, 446, 297 (2007)

Nonlinear circuit oscillators have non-degenerate energy level spacings and hence behave just like 2-level atoms

Slides from Dave Schuster (U.Chicago)



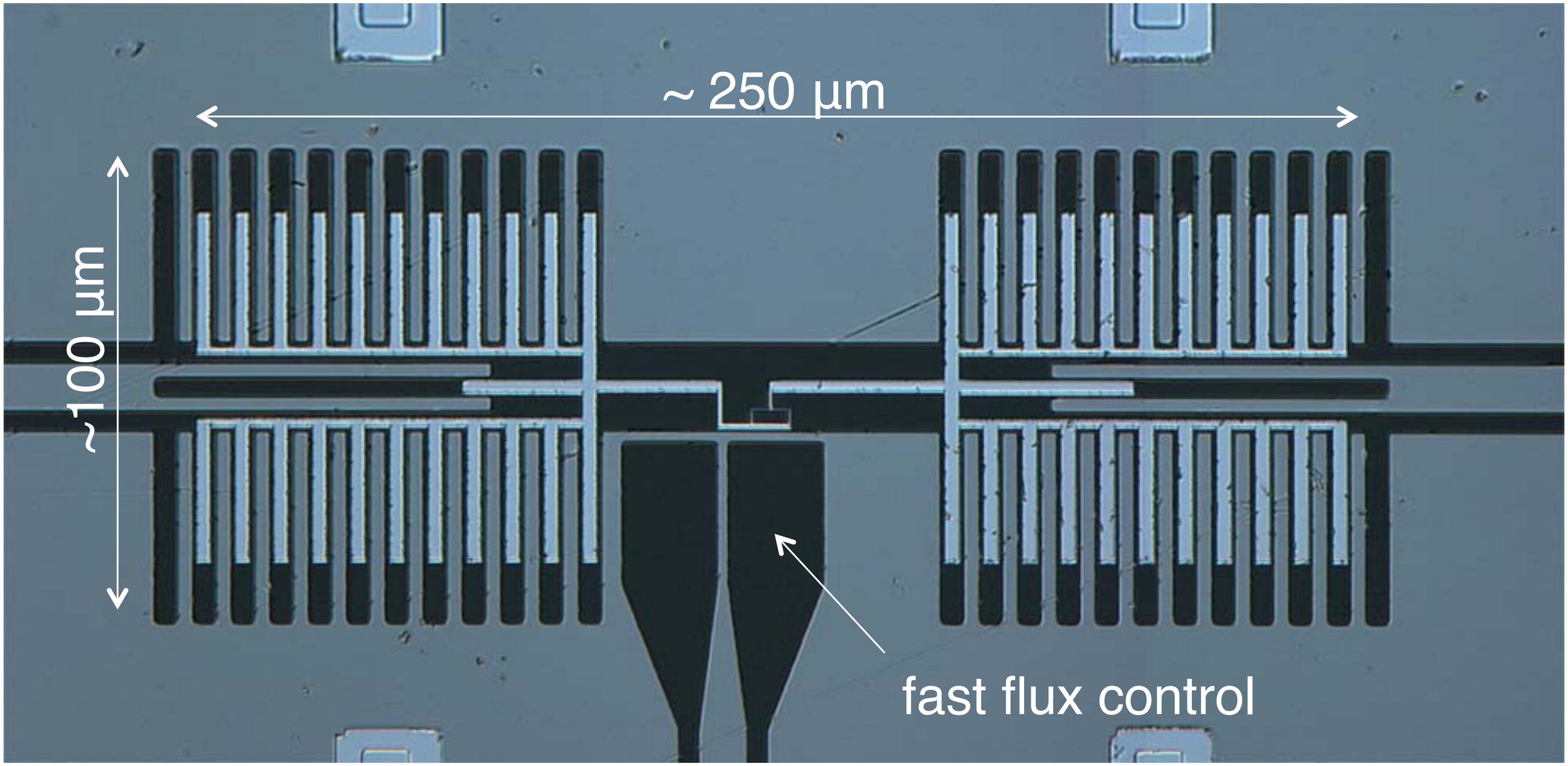
Transmon qubit based on the Cooper pair box
J.Koch, e.al, Phys.Rev.A76, 042319 (2007)



QND detectors developed for high fidelity quantum computing qubit readout.
B.R. Johnson, et.al, Nature Physics 6, 663-667 (2010)

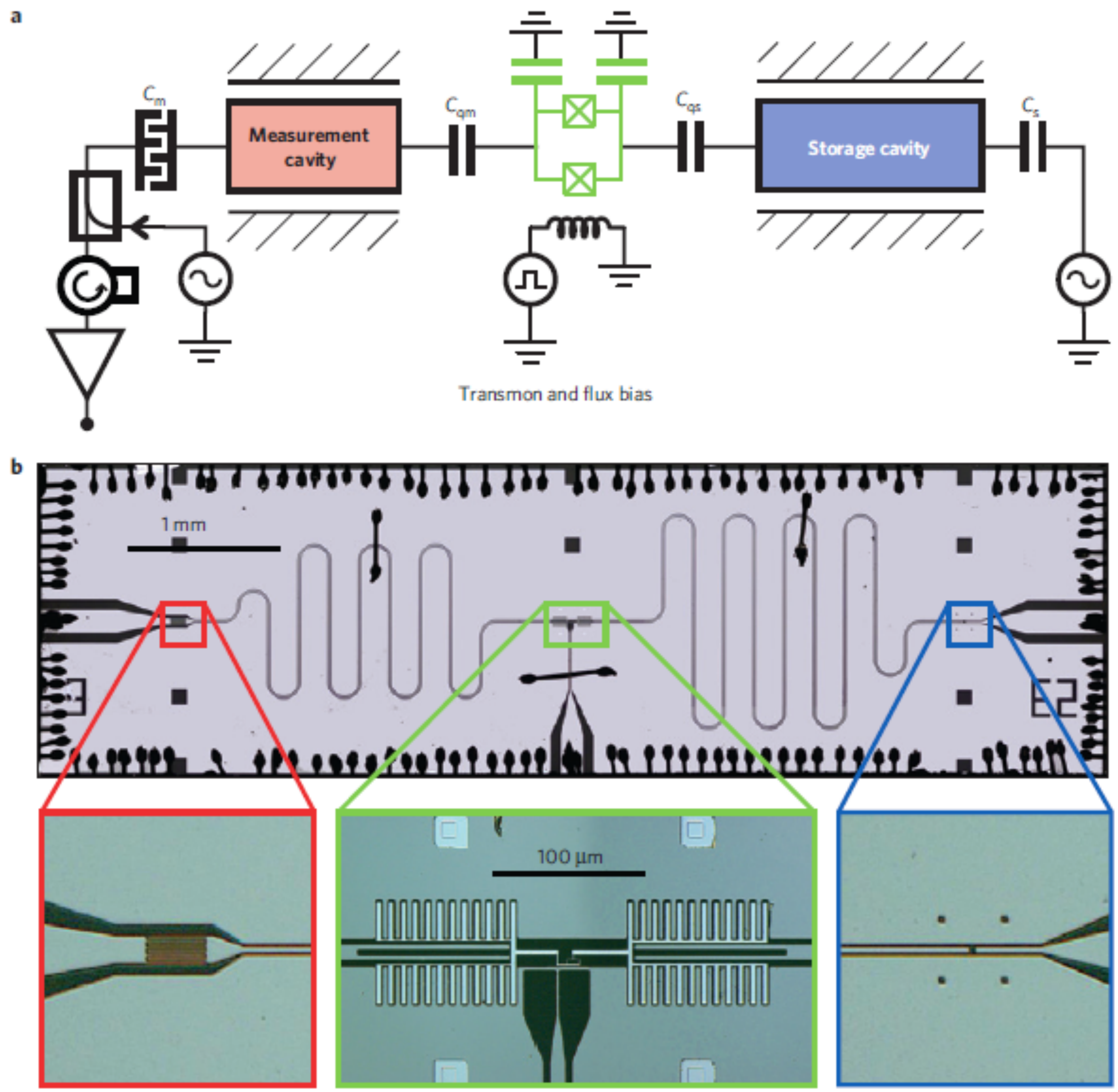
The sarantapede

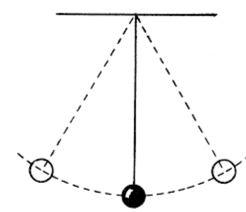
- An end-coupled "transmon" qubit with ~40 legs



QND Detector = qubit + fast cavity

Readout frequency shift

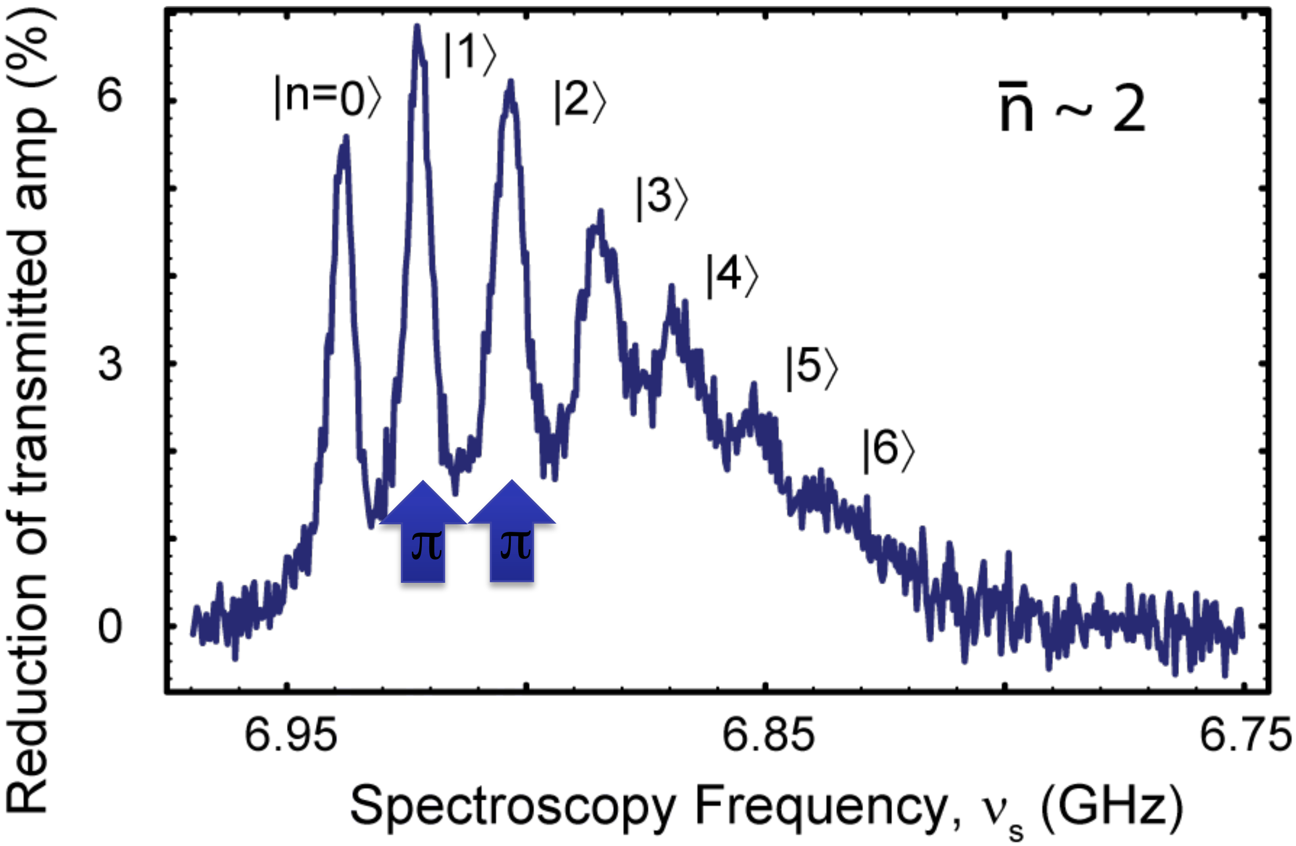




Axion DM

Sensing photon number with a qubit

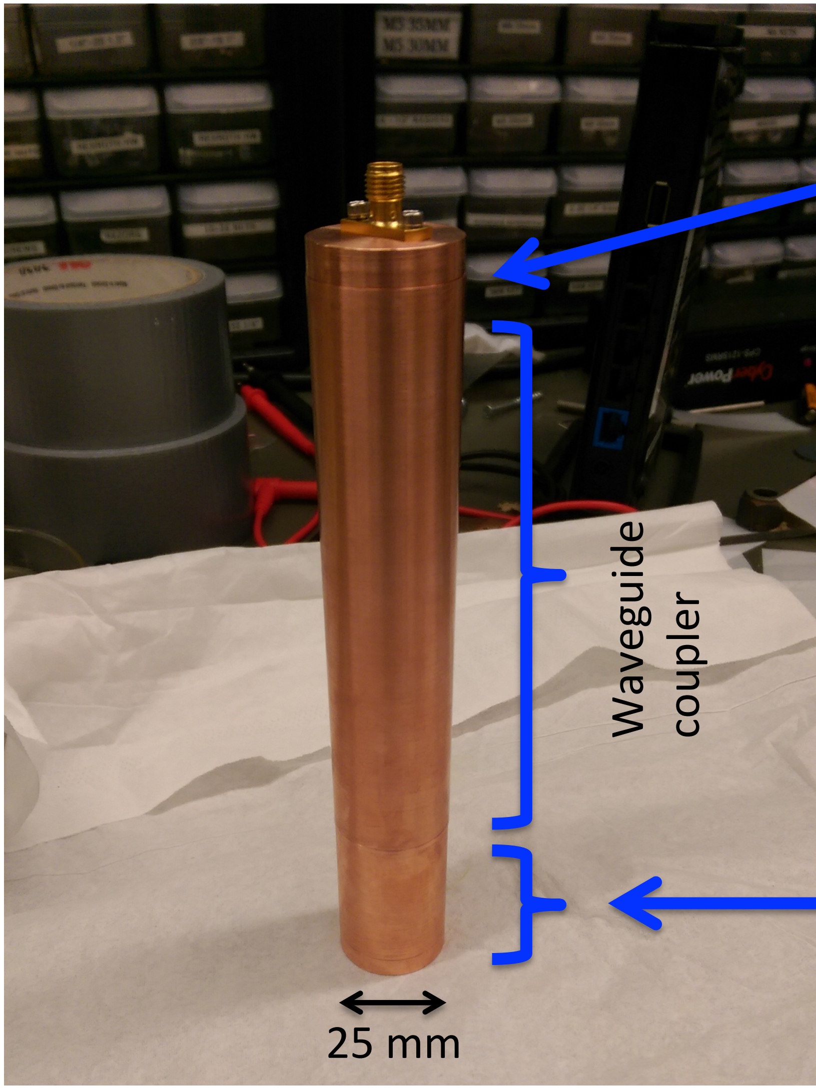
$$H \approx \hbar\omega_r a^\dagger a + \frac{\hbar}{2}(\omega_a' + 2\chi a^\dagger a)\sigma_z$$



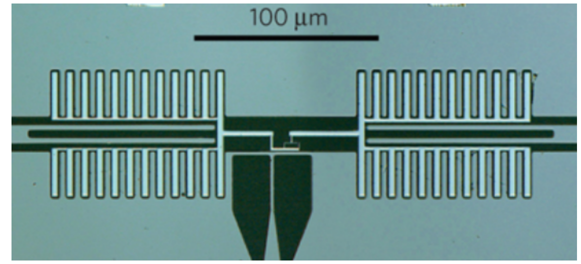
- Qubit transition frequency depends on photon number in cavity

Theory: J. Gambetta, A. Blais, …, S. Girvin, and R. J. Schoelkopf, *PRA 94 123602 (2005)*
Experiment: D. I. Schuster, … , S. M. Girvin, R. J. Schoelkopf, Nature (London) **445** 515 (2007)

Prototype for 10 GHz axion QND detector



Akash Dixit, Aaron Chou, David Schuster (UC),
R&D in progress

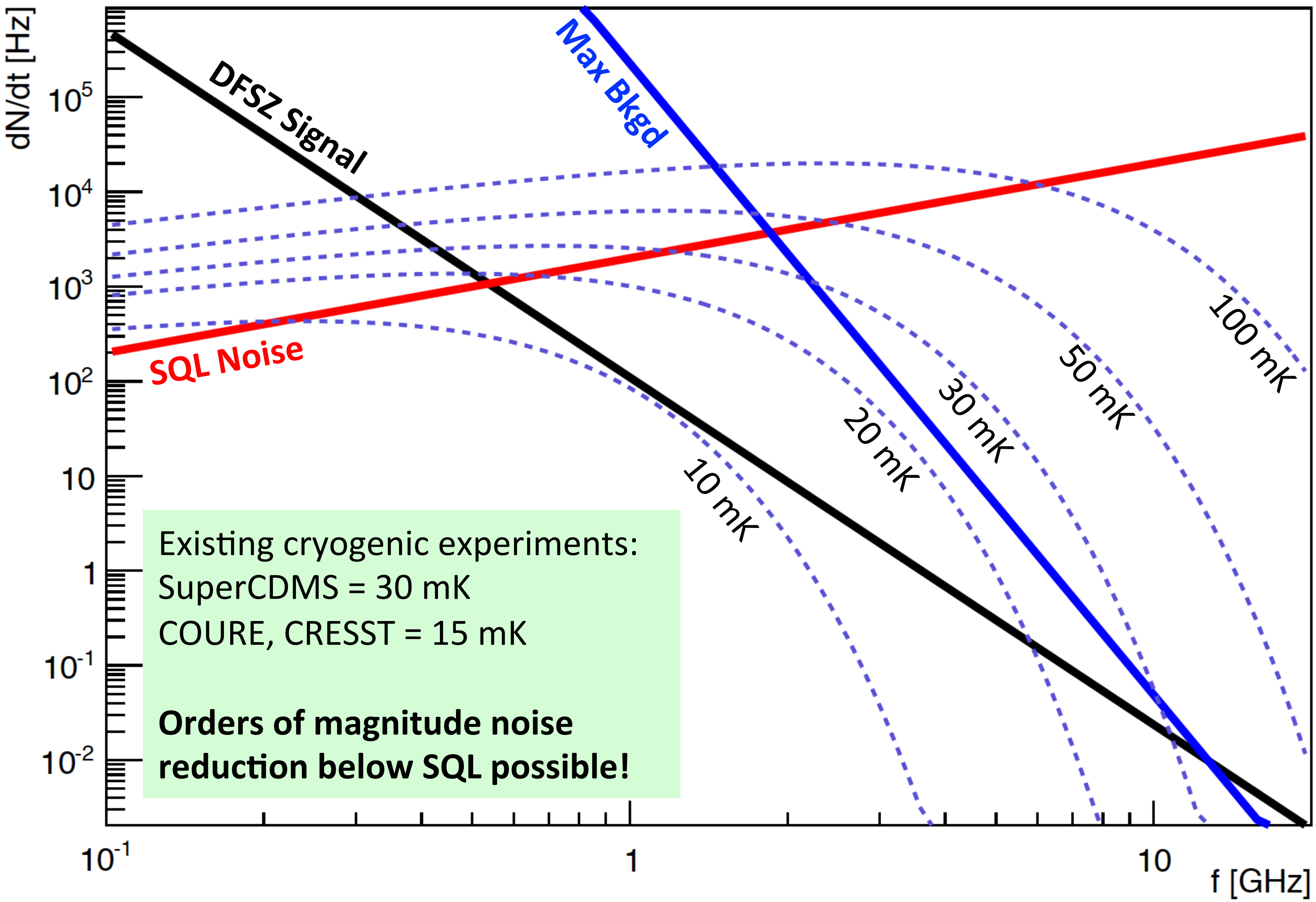


Superconducting qubit in field-free bucking coil region acts as an amplitude→frequency transducer for QND measurements.

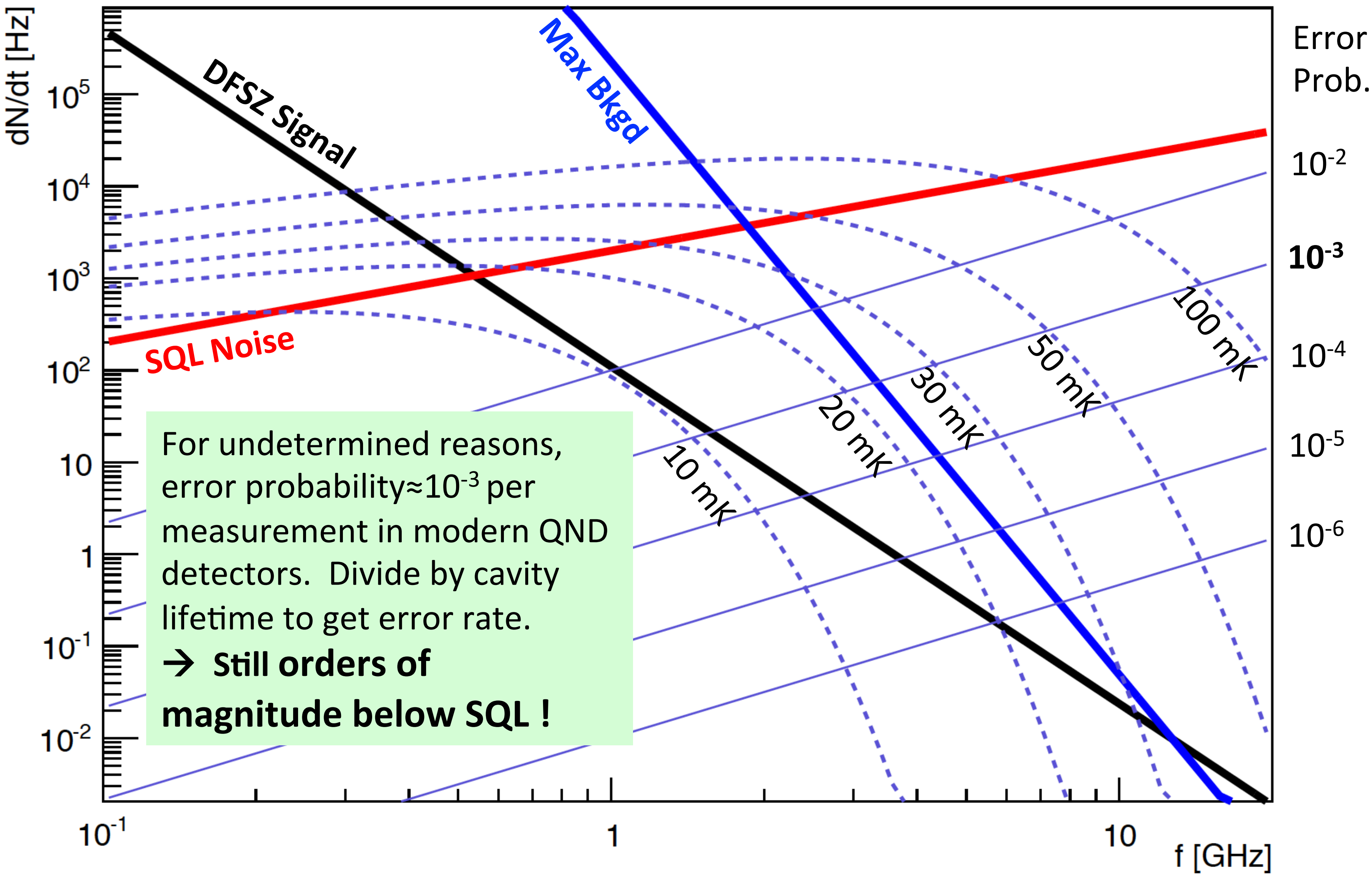
Qubit frequency shifts by 10 MHz per photon deposited in axion cavity. **Successful "spin-flip" of qubit confirms presence of cavity photon.**

Axion scattering cavity dipped into high B-field region

Thermal photon background rates are negligible



Another background "photon" source: QND false positives from read errors



Take-aways

- The strong CP problem is one of the great unsolved fine-tuning problems in the Standard Model
- The Peccei-Quinn axion model simultaneously solves strong CP and guarantees axion dark matter.
- **ADMX-G2 uses demonstrated technology and is the only currently operating experiment with sensitivity to QCD axions.**
- Detailed information about the dark matter phase space structure is available immediately after initial discovery
- Active interdisciplinary R&D is underway to address the quantum noise problem at higher frequencies.
  - Zero-point energy has to do with measurement back-reaction, and it is not obviously a "vacuum" energy since it can be avoided